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Linkage of Truck-and-shovel Operations to Short-term Mine Plans Using Discrete Event Simulation

by

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ABSTRACT

The scope of this research is concerned with improving truck-and-shovel systems' efficiency using simulation. The major shortcomings of the current simulation models reviewed in literature are: a) considering shovels as continuously working equipment, b) modeling the system based on a shovel's production requirements, and c) considering only the total tonnage of material hauled with neither any measure of material quality nor a link to the mine production schedule.

The objective of this study is to develop, implement, and verify a simulation model to analyze the behavior of a truck-and-shovel haulage system in open-pit mining in conjunction with short-term plans. The simulation model imitates the complex truck-and-shovel system, and considers the uncertainties associated with the operations of trucks and shovels. It guarantees that the operational plans will honor the optimum net present value obtained in the scheduling phase. The simulation model is verified by a case-study measuring key performance indicators of the truck-and-shovel haulage system.

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Last but not least, my heartfelt appreciations go to my husband and the love of my life, Behrang, for his unconditional love, care, understanding, and support. To him I dedicate this thesis.

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LIST OF ABBREVAITIONS

Parameters

NPV	Net Present Value
OR	Operations Research
KPI	Key Performance Indicator
LP	Linear Programming
MIP	Mixed Integer Programming
MILP	Mixed Integer Linear Programming
LOM	Life Of Mine
VBA	Visual Basic for Applications
FPC	Fleet Production and Cost
NN	Neural Network
MR	Multiple Regression
MTBF	Mean Time Between Failures
MTTR	Mean Time To Repair
MWT	Magnetic Weight Recovery of Iron
ID	Identification

LIST OF NOMENCLATURE

Sets

$I = \{1,...,I\}$	Set of mining-faces.
$J = \{1,...,J\}$	Set of shovels.
$K = \{1,...,K\}$	Set of types of trucks.

Indices

$i \in I$	Index for mining-faces.
$j \in J$	Index for shovels.
$k \in K$	Index for types of trucks.

Parameters

$MAT_i \in \{0,1\}$	Current material type of mining-face *i*. It is equal to 1 if current material type of mining-face *i* is ore; otherwise it is equal 0.
ORE_i	Remaining ore tonnage at mining-face *i* (tonnes).
$WASTE_i$	Remaining waste tonnage at mining-face *i* (tonnes).
$AVL_i^{face} \in \{0,1\}$	Availability of mining-face *i*. It is equal to 1 if mining-face *i* is available; otherwise it is equal to 0.
$AVL_j^{shovel} \in \{0,1\}$	Availability of shovel *j*. It is equal to 1 if shovel *j* is available; otherwise it is equal to 0.
$SHCAP_j^{\max}$	Maximum production capacity of shovel *j* (tonnes per hour).

$SHCAP_j^{\min}$	Minimum production capacity of shovel *j* (tonnes per hour).
NUM_k	Number of available trucks of type *k*.
$COMP_{jk} \in \{0,1\}$	Compatibility of truck *k* with shovel *j*. It is equal to 1 if truck *k* is compatible with shovel *j*; otherwise it is equal to 0.
CT_{ik}^{ore}	Cycle time of truck type *k* transferring ore from mining-face *i* to the crusher (seconds).
CT_{ik}^{waste}	Cycle time of truck type *k* transferring waste from mining-face *i* to the waste dump (seconds).
CAP_k^{ore}	Capacity of truck type *k* when transferring ore (tonnes).
CAP_k^{waste}	Capacity of truck type *k* when transferring waste (tonnes).
GR_{il}	Grade of element *l* at mining-face *i* (%).
UB_l	Upper bound of grade blending for element *l* (%).
LB_l	Lower bound of grade blending for element *l* (%).
$PMAX$	Maximum processing capacity of the crusher (tonnes).
$PMIN$	Minimum processing capacity of the crusher (tonnes).
MC_{ij}	Trip cost of shovel *j* travelling from its current location to mining-face *i* ($).
TRC_{ik}^{ore}	Trip cost of truck type *k* travelling from mining-face *i* to the crusher ($).
TRC_{ik}^{waste}	Trip cost of truck type *k* travelling from mining-face *i* to the waste dump ($).

DC	Cost of deviation from target production ($ per ton).
T	Planning time duration (hours).

Decision Variables

$a_{ij} \in \{0,1\}$	Binary integer decision variable representing assigning of shovel *j* to mining-face *i*. It is equal to 1 if shovel *j* is assigned to mining-face *i*; otherwise it is equal to 0.
n_{ik}^{ore}	Continuous decision variable representing number of trips of truck type *k* from mining-face *i* to the crusher.
n_{ik}^{waste}	Continuous decision variable representing number of trips of truck type *k* from mining-face *i* to the waste dump.
x_i	Extracted material tonnage from mining-face *i* (tonnes).

CHAPTER 1

INTRODUCTION

1.1 Background

The fundamental objective of any mining project is to maximize mine profit by extracting ore at the lowest possible cost over the mine life (Askari-Nasab et al., 2007). Especially in open-pit mines, acquiring the optimal production with minimum cost is an essential issue, because open-pit mine operations are highly capital intensive.

Open-pit mining is the common type of surface mining that produces 85% of minerals in North America (Hartman and Mutmansky, 2002). This type of mining is more popular due to advantages such as greater safety and mechanically easier operations.

Operating costs, as one of the major expenditures in open-pit mines, mainly incur in development and production phases. A significant portion of operating costs is related to operations of equipment and machineries involved in material-handling-and-haulage systems. Since material-handling-and-haulage machineries are among a mine’s most expensive necessities, one of the most challenging practices is to use them effectively.

The most commonly used material-handling-and-haulage system in open-pit mines is a truck-and-shovel system. This system has been the most widely used throughout the world since the 1930s (Raj et al., 2009).

Haul trucks and loading shovels, which are key resources of open-pit mining operations, represent a significant capital cost. Very large capital investments are needed to purchase and replace these fleets, and also maintenance costs are high. Although using truck-and-shovel haulage systems requires a large capital investment, it has significant advantages: they are safe, inexpensive to operate, and lead to high productivity, which makes them popular.

Trucks and shovels constitute 50 to 60 percent of an open-pit mine’s overall operating costs (Ercelebi and Bascetin, 2009). Because of this, a lot of effort has been directed to utilize trucks and shovels efficiently. An efficient truck-and-shovel system reduces hauling, operating, and maintenance costs, while meeting production targets and providing a steady and reliable feed of material.

Nowadays, with increasing equipment and fleet size and capacity, increasing haul distances, deepening pits, and a more competitive mineral market, the problem of improving the use of available fleet becomes even more important and challenging. The problem is challenging because truck-and-shovel systems are complicated and the aforementioned factors contribute to the complexity of the system. Another reason for the complexity is the uncertainties in the operations of trucks and shovels. These uncertainties include the velocity of fleet that affects the cycle times, and truck and shovel reliabilities. With a larger view to the problem, these factors have an impact on overall mine production. Ignoring such uncertainties in mine operations could result in deviations from the optimal plans. Any deviation from the production targets because of operational uncertainties increases the overall cost.

Decisions about truck-and-shovel systems should be consistent with those made in the production scheduling phase. Production scheduling is an important aspect of mine planning and design. Long-term production scheduling usually aims to maximize the net present value (NPV). At this level, optimal long-term plans are generated. These plans define the yearly production schedules. In the short-term, to minimize deviations from production targets, production scheduling is done based on long-term plans. The result is optimal short-term plans that define monthly, weekly, or even daily production schedules to deliver the designated tonnes and grades to the processing facilities. In both long-term and short-term schedules, the sequence of blocks that has to be mined over time is a critical consideration.

Truck-and-shovel systems are components of a mine and have great potential to create savings. It is important to analyze their behavior in conjunction with short-term plans. This approach enables us to reach the optimal production target in short-term and secure the main objective of the mining operation, which is maximizing NPV, in long-term.

1.2 Statement of the Problem

Because of the size of open-pit mines, the revenue and the costs are enormous. One of the major costs for an open-pit mine is for the material-handling-and-haulage system. The truck-and-shovel system is the most popular system because of its flexibility in removing large volumes of material. The economics of today's mining industry requires mining companies to put more effort into the efficient usage of trucks and shovels.

One of the primary problems in open-pit mining is the proper use of loading and hauling fleet, in order to obtain the maximum efficiency and minimum cost. The ability to evaluate the performance of the truck-and-shovel systems is very important, because any improvement would save a substantial amount of money. Another major issue in open-pit mining is selecting trucks and shovels to satisfy the production target. This problem occurs in the mine design and operations phases.

The proposed research lies within the area of applied operations research (OR). The research problem is classified as application of discrete-event simulation in open-pit truck-and-shovel operational planning. This study develops and implements a simulation model to represent a truck-and-shovel system employed in an iron ore open-pit mine. The model simulates the whole mine in sufficient detail, with the focus on the truck-and-shovel system. Activities involved with trucks and shovels during loading and hauling operations are emphasized.

Two main sub-problems are considered in this research. First is the equipment selection problem, in which the numbers of trucks and shovels are determined. The second is the behavior of the designed system with the selected amount of equipment. Using defined key performance indicators (KPIs), the efficiency of the system is measured. One of the most important KPIs is the truck cycle time. Since a typical truck-and-shovel system is considered, a truck cycle time is comprised of the time it takes the truck to travel to the mining-cut location, be loaded by the shovel, travel to the destination facility, dump, and travel back to the pit-exit point.

The iron ore open-pit mine considered in this study consists of a pit with an exit point. Also, there are three types of destinations:

1. Waste dumps
2. Stockpiles
3. Processing plants (crushers)

The proposed model deals with the uncertainties associated with the operations of trucks and shovels. These uncertainties include truck velocity during day and night shifts, shovel velocity, shovel's bucket capacity, dump time, and failures of fleets and facilities.

One of the most successful outcomes of this study is that the optimal short-term schedule generated for the mine is now directly linked to the simulation model. This approach guarantees that the designed truck-and-shovel system's operations will follow mine planning's main objective, which is maximizing NPV. Eivazy & Askari-Nasab (2012) have produced the optimal short-term schedule for the same mine. They have used mathematical programming to generate the optimal short-term open-pit mine production schedule. Their approach uses a mixed integer linear programming (MILP) model. They have also applied a hierarchical clustering algorithm to aggregate blocks into scheduling mining units, referred to as mining-cuts.

This research goes beyond the existing short-term plan and considers the ability to send ore to stockpiles when a crusher is down. The truck-and-shovel system performance is assessed under this new assumption as well.

The following research question drives this dissertation:

> *Considering the uncertainties associated with the operations of trucks and shovels, is it possible to build a linkage between the optimal short-term mine schedule and the truck-and-shovel material-handling-and-haulage system, which would improve the use of these resources while meeting short-term production targets and complying with the optimal block extraction sequence?*

This research also deals with the problem of allocating trucks and shovels to mining-faces. For this purpose a mathematical programming model is developed and presented.

1.3 Summary of Literature Review

In this section, a summary of research done on truck-and-shovel haulage systems is presented. This is a summary of a detailed literature review presented in Chapter 2.

Different methods for modeling truck-and-shovel systems are reported in literature. Some of these methods rely on empirical rules and some are highly mathematical, requiring significant computational effort. None of these methods can comprehensively consider all aspects of truck-and-shovel systems. Most approaches usually ignore the stochastic nature of the truck-and-shovel operations.

Among current methods, simulation is widely accepted as a way to assess the performance of mining operations, because it makes it possible to incorporate the system's inherent variability and complexity. The widespread use of simulation techniques is explained by the fact that the models usually are easier to understand. Also compared to other OR techniques, simulation requires less complex mathematical modeling and formulation. Simulation has become even more popular as computers have become more powerful and inexpensive.

The other commonly used approaches in the literature are mathematical programming and stochastic methods such as queuing theory and stochastic programming. Regarding mathematical programming methods, in conventional linear programming (LP)-based approaches, stochastic parameters are considered in constraints and these constraints are met 50% of time. In stochastic programming, the uncertainty is explicitly included in the numerical solution and constraints can be satisfied by an explicitly expressed confidence (Ta et al., 2005).

Although mathematical programming-based models have been developed for truck-and-shovel systems since the 1970s, most have some shortcomings. They do not take into account the stochastic nature of the truck-and-shovel systems, the economic parameters, and the multi-time-period nature of the mining operations (Gurgur et al., 2011), so they are usually combined with simulation models or other stochastic approaches, as seen in studies by Temeng et al. (1997), Fioroni et al. (2008), and Yuriy and Vayenas (2008).

Some other studies have developed models based on mathematical programming approaches to optimize production scheduling and truck dispatching problems in the same framework, such as works by Yan and Lai (2007), Yan et al. (2008), and Gurgur et al. (2011).

Simulation studies about truck-and-shovel systems are mostly implemented for specific cases. Each of these studies tries to apply the simulation modeling for a real mine such as models developed by Sturgul and Eharrison (1987) for a surface mine in Australia, Peng et al. (1988) for an iron ore mine in northeast China, Forsman et al. (1993) for a copper ore mine in northern Sweden, and Awuah-Offei et al. (2003) for a typical hard rock auriferous mine in Ghana. The majority of these simulation studies, such as those by Wang et al. (2006) and Burt and Caccetta (2007), are only evaluating truck dispatching rules, while others, such as Karami et al. (1996) and Awuah-Offei et al. (2003), try to also consider the operations involved in the truck-and-shovel system.

Some studies have applied the queuing theory to analyze truck-and-shovel haulage systems in open-pit mining. The first application of queuing theory in mining context was done by Koenigsberg (1958). His work is followed by Carmichael (1986; 1987), Kappas and Yegulalp (1991), Muduli and Yegulalp (1996), Czaplicki (1999), Trivedi et al. (1999), Alkass et al. (2003), Krause and Musingwini (2007), Ercelebi and Bascetin (2009), and Ta et al. (2010).

There is limited literature on stochastic programming applied in the field of mining. It seems that only Ta et al. (2005) have used the stochastic programming directly in evaluating a truck-and-shovel system .

The limitations in the current research on truck-and-shovel systems in open-pit mining are:

- Few details are considered in truck-and-shovel models. Considering more details makes the models complicated, which in return means that more time, money, and computer memory is needed to find a solution.
- The stochastic nature of the truck-and-shovel systems is usually treated as deterministic. This weakness is mostly seen in mathematical programming techniques.
- In almost all of the literature, the system is modeled based on the shovel production requirement, which is stated as the shovel's hourly production rate. With this approach, the shovels are assumed to work continuously and the main focus is on the operations of trucks only.
- In almost all of the literature, the source of material is defined as a mining-zone or a mining-face. This approach treats each zone as a single complete unit that has single grade and tonnage characteristics. This imposes the assumption that all blocks in a mining-zone are identical. But in the real world, trucks and shovels extract mining blocks which have distinct ore and waste percentages and grades.
- A huge portion of research focuses on the truck-and-shovel system as a closed system. Almost no research considers the interactions with other systems in the mine such as processing systems. They do not take into account the activities and uncertainties of these systems' operations.

The developed simulation model in this research represents a truck-and-shovel system with fairly enough details, and successfully studies the uncertainties of truck-and-shovel operations. Considering more of the system's details requires more time and computational memory.

The system's design and performance analysis is implemented based on the short-term mine plan, which is derived from overall mine plan requirements according to the economic and operational objectives, not only the shovel's requirements. This is one of the most significant contributions of this research.

Moreover, since the simulation model is linked to the short-term plans, a mining unit which is smaller than a mining-zone or a mining-face is defined. The mining-cut is defined as a mining unit with distinct location, tonnage, and grades. This approach also takes into account the precedence between mining-cuts, which is another important contribution of this research.

The model also considers the crushers as units that interact with the truck-and-shovel system. In addition, the proposed model consists of sub-models representing the reclamation process.

1.4 Objectives of the Study

In an open-pit mine, in the truck-and-shovel haulage systems, the production capacity of the truck should match that of the shovel. However, the trucks are not being used effectively. If the production capacity of the set of shovels is bigger than that of the set of trucks, the shovels have to wait for the trucks to come available. If the production capacity of the set of trucks is bigger than that of the set of shovels, the trucks have to wait for the shovels to come available. A combination of both problems can also occur in a truck-and-shovel system. Either way, the system is inefficient, with mismatched capabilities. (Castillo and Cochran, 1987).

The typical objective of truck-and-shovel haulage system models presented in the literature is to maximize the mine's production utilizing the available trucks and shovels, or to minimize the number of trucks while considering the production target over an operational period. On the other hand, mine planning's main objective is to maximize NPV over the mine's life. With these definitions of objective functions, solutions obtained from truck-and-shovel models usually do not guarantee the optimal NPV. To support the main objective of the mine planning, truck-and-shovel models should be considered along with short-term and long-term plans (Gurgur et al., 2011).

The objectives of this research are:

- To develop, implement, and verify a simulation model to analyze the behavior of a truck-and-shovel haulage system in open-pit mining in conjunction with short-term plans. This model imitates the complex truck-and-shovel system, and considers the uncertainties associated with the operations of trucks and shovels. It guarantees that the operational plans will honor the optimum NPV obtained in the scheduling phase.
- To determine the necessary numbers of trucks and shovels to meet the production target and honor block extraction sequences. This objective is achieved by evaluating different scenarios. Each scenario has different numbers of trucks and shovels, and the decision is made based on the production target and other KPIs. Also, the effect of randomness in reliabilities of trucks, shovels, and crushers on the required number of resources is examined.
- To study the possibility of reducing truck cycle times, which is one of the major KPIs. Failures of crushers are one of the factors that increase the truck cycle time, because failures make trucks wait for crushers to be repaired. An alternative to waiting for repairs is to send the material to stockpiles. This alternative is also included in this study.
- To optimally allocate trucks and shovels to mining-faces. The decision about allocating trucks and shovels is made when required, for example, at the beginning of each period, when a truck or a shovel breaks down, or when a mining-face completely depletes. For this purpose a MILP model

is developed. The ultimate goal is to integrate the mathematical programming model and the simulation model, which requires further research.

1.5 Context and Scope of the Work

A precise evaluation of a truck-and-shovel system's performance is a challenging task because of the system's complexity. Truck-and-shovel systems are complicated due to the huge number of operations that are in progress simultaneously. Also, uncertainties associated with the operations of trucks and shovels make the study of the system more challenging.

Compared to other OR methods, which cannot deal comprehensively with the stochastic variables, simulation is a handy and successful OR tool to study stochastic systems. Simulation models enable the user to conduct numerical experiments to study the system in detail and understand its behavior under different conditions (Kelton et al., 2007). While simulation may not be the only tool to model and study the system, it is the choice of this research. The reason for this is that the simulation model can be allowed to become quite complex to represent the system faithfully. Other methods require stronger simplifying assumptions about the system to enable an analysis.

A simulation model can be defined as a simplified representation of a real system. In designing a simulation model, a decision should be made as to how much detail of the real system should be represented in the model. The goal is to design a simulation model that represents the system in enough detail and can be solved in a reasonable time, rather than having a complicated model which is not affordable in terms of either time or money. Therefore, in this research some simplifying assumptions are considered. Some of the assumptions and details are as follows:

- A typical truck-and-shovel system is considered, in which shovels dig mining-cuts and load them to the trucks, trucks transfer the material to the pit-exit and from there take the material to the predetermined destination according to the short-term plan. The trucks dump their loads at the destination facility, travel back to the pit-exit, and from there travel to another mining-cut location.

- All trucks are identical, and all shovels are identical.
- A reclamation process from stockpiles to appropriate crushers is considered.
- Short-term production schedule and mining-cut extraction sequences are the basic inputs and are taken into account directly in the model.
- Stochastic variables in the operations of trucks and shovels are included in the model. The stochastic variables are represented by probability density functions which are generated based on the historical data. All downstream failures in a processing plant are combined and represented with one stochastic variable.
- The focus of the research is on the truck-and-shovel material-handling-and-haulage system. Therefore, the study of activities involved in processing plants is out of this research's scope.

As stated above, the main purpose of this study is to design and develop a truck-and-shovel haulage system for an iron-ore open-pit mine. The system operates in conjunction with short-term plans. The simulation model mimics the system in detail and tries to consider uncertainties as much as possible.

From a hierarchical point of view, this research addresses a problem in open-pit mining. Open-pit mining is a category of the surface mining method. This research creates a linkage between strategic and operational planning levels by considering excavation and haulage operations. For excavation and haulage, truck-and-shovel systems are chosen and simulation modeling is implemented.

This research also studies the allocation problem of trucks and shovels. The developed MILP model is proposed under certain assumptions which are explained in detail in Chapter 3. The coding, solving and verification of the model is out of this study's scope and needs further research. The main focus of this research is on the simulation modeling of truck-and-shovel systems. The mathematical programming model is developed at the mining-face level and the simulation model is at the mining-cut level. Solving the MILP model and integrating it with a simulation model is recommended for future research. Figure 1 shows the diagram of the scope of the work.

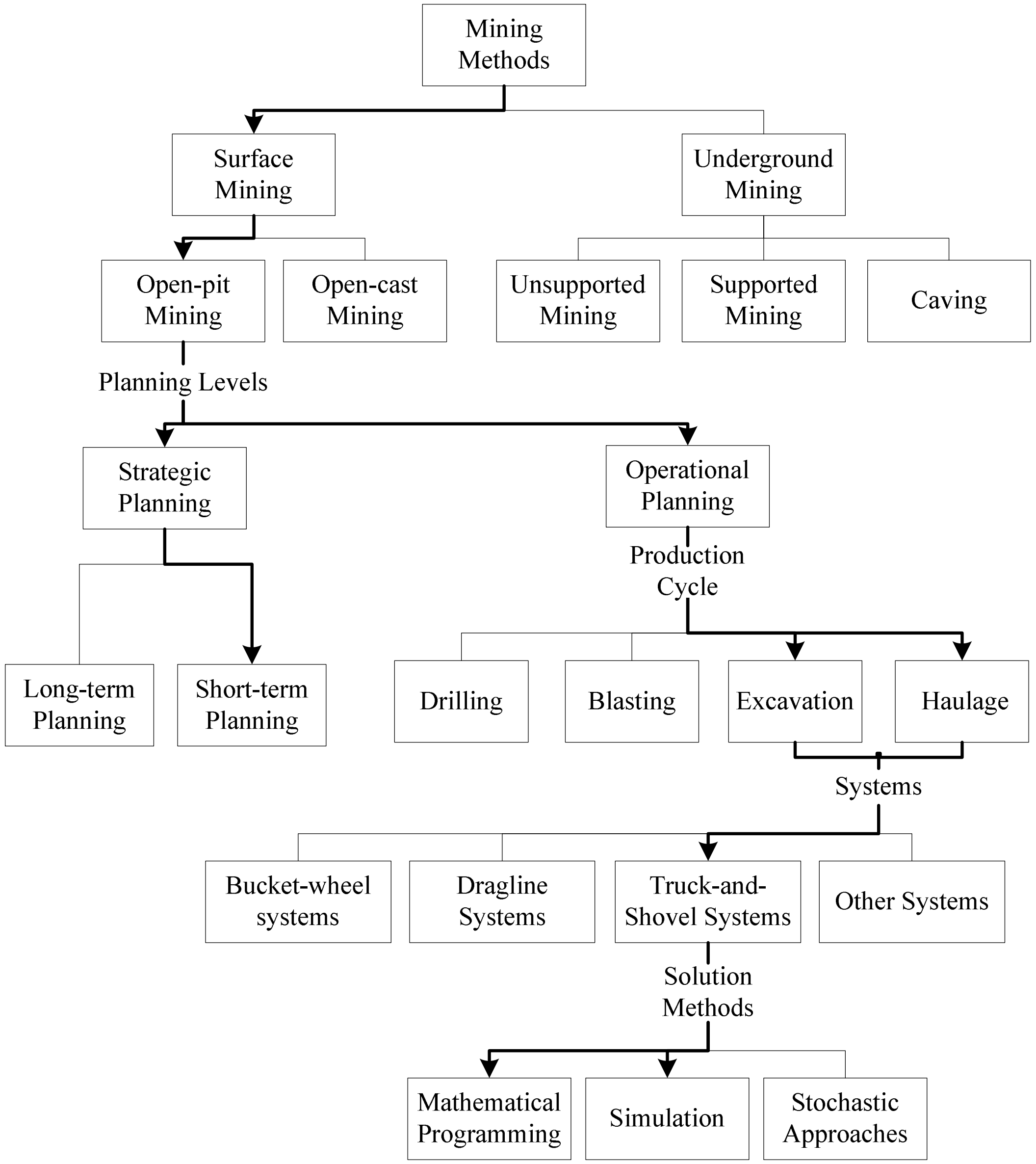

Figure 1. Diagram of the scope of the work from a hierarchical point of view

1.6 Research Methodology

Due to the complexity of truck-and-shovel systems, simulation is used to study the system. Some simplifying but realistic assumptions are considered to obtain fairly accurate results. The details of the assumptions are presented in Chapter 3.

The following is a summary of the research tasks involved in the study:

- A thorough literature survey on modeling truck-and-shovel systems is carried out with focus on different methodologies. The survey involves a comprehensive review of the allocation and dispatching problems, and the applications of discrete-event simulation in mining studies.
- Using mathematical programming, a theoretical framework focuses on the allocation problem. The developed MILP model optimally allocates trucks and shovels to mining-faces.
- A real world truck-and-shovel system is analyzed to obtain insight into the activities and prevalent factors involved in truck-and-shovel systems. This step establishes the research objectives and KPIs.
- The simulation model is conceptualized using trucks and shovels as the system's resources. The conceptual model studies truck-and-shovel operations, as well as reclamation operations, in a typical truck-and-shovel system.
- Data analysis is performed on historical dispatching data gathered from a Jigsaw dispatching database. Suitable probability density functions are fitted on the data.
- Based on the developed conceptual simulation model, the actual model is developed using Arena (Rockwell Automation, 2010) simulation software. In addition to the main model, which represents the operations of trucks and shovels, different aspects of the system are represented as sub-models.
- The proposed simulation model is verified to confirm that the actual model is correctly implemented with respect to the conceptual model. This step is

necessary to assure that the proposed model matches specifications and assumptions considered for the research. The validation of the simulation model is recommended for further research.

- In the final phase, the model is tested on an open-pit mine. The performance of the system is evaluated extensively.

One of the major advantages of the proposed simulation model is that the model considers the randomness of operations of trucks and shovels and their reliabilities. The simulation model also considers the detailed operation of trucks and shovels successfully, something other methods cannot do. This approach enables us to assess performance parameters of different truck-and-shovel systems in detail.

The proposed approach studies the truck-and-shovel system in two major sections:

- The first section deals with the equipment selection problem, specifically, the problem of determining the numbers of trucks and shovels. In this section, different scenarios with different numbers of trucks and shovels are examined to select the best scenario. The dominant criterion used to assess each scenario is the ability to meet the production target. The production target is generated via short-term production scheduling. The other two criteria are the levels of use of trucks and shovels. This part of research is completed in three evolutionary procedures as follows:

1. In the first procedure, the truck-and-shovel system without failures is considered. Also, the failures of crushers are ignored.
2. In the second procedure, all failures are considered. Failures include two types of truck failures, shovel failures, and crusher failures. All failures are introduced as random elements in the system.
3. In the third procedure, based on the results from previous step, possible maintenance schedules are planned for trucks, shovels, or both. If the

utilization of trucks or shovels obtained in second step, show significant variations in different periods, then this step is carried out.

- As the numbers of trucks and shovels is determined in the first part, this part deals with further analysis of the performance of the designed truck-and-shovel system. Among the KPIs that are assessed are truck and shovel utilizations; truck cycle time; queue lengths; truck waiting times; ore and waste tonnage delivered to different facilities; and grade of major elements including phosphor, sulfur, and iron at different facilities. Further analysis is also done to assess some of the KPIs separately for different working shifts. In this part, two different mining scenarios are taken into account as follows:

1. The first scenario is the basic mining system, the same as the one used in the equipment selection phase.
2. In the second scenario, an alteration is applied to the existing system. It is considered that in the case of a crusher failure, trucks assigned to the failed crusher deliver their loads to the corresponding stockpile. Delivered material during this process can be reclaimed during the subsequent period.

The simulation model is verified by ignoring the uncertainties included in the model and running the model for sample mining-cuts. Considering all parameters as deterministic values, the results are compared with time calculations performed by hand. The main criterion for this comparison is truck cycle times, because as long as truck cycle times are accurate, the model is complete. Also, the tonnage of the sample mining-cuts is considered as another criterion for the verification process.

One of the significant problems in any stochastic simulation modeling is determining the proper number of replications. The proposed simulation model uses half-width analysis. As the outcome, a 95% confidence level is used to evaluate the results.

Further details of the mine under study, methodology, and simulation logic are discussed in chapter 4.

1.7 Scientific Contributions and Industrial Significance of the Research

The main contribution of this work is that it integrates short-term production scheduling and operations of a truck-and-shovel system for open-pit mining in a simulation framework. This includes selecting the required numbers of trucks and shovels based on the short-term mine plan, which is derived from overall mine plan requirements according to the economic and operational objectives, rather than from the shovel's requirements, which is more common in the literature (Gurgur et al., 2011).

Regarding links to a short-term schedule, another outstanding achievement is that the sequence of block extraction and blocks' precedence is taken into account in the proposed simulation model. This study considers mining-cuts with exact coordinates, tonnage, grades of elements, and other identifying characteristics. This approach gives a more accurate view of the system, rather than just considering the production rate of shovels, which was the approach used in previous research.

This approach also enables us to examine different production schedules to assess their effect on the haulage system units. Also, different block extraction sequences can be examined through the proposed approach by evaluating the performance of the truck-and shovel system. The simulation model developed in this study directly deals with the mining-cut characteristics. This procedure enables us to consider grade uncertainty, and analyze their effect from the operating point of view. Grade uncertainties are very important uncertain factors in mine planning.

1.8 Organization of Thesis

Chapter 1 is a general overview of the research. It discusses the background of the study, followed by the problem statement, objectives, context, scope, proposed methodology, and contributions of the research.

Chapter 2, the literature review, provides an overview of common methodologies and approaches used in studying truck-and-shovel systems including mathematical programming, simulation, and other stochastic methods. It presents the background about the application of simulation in the mining industry. It also provides background about long-term and short-term mine planning as the basis for the proposed simulation model.

Chapter 3 contains the theoretical framework for the mathematical programming formulation to optimize the allocation of trucks and shovels. The initial part of this chapter provides the mathematical model and formulations with definitions of objective function and constraints. This chapter also describes the characteristics of the simulated truck-and-shovel system. It contains a detailed explanation of the operations of trucks and shovels and the logic behind the proposed simulation model. It also includes specifications of the mine under study as well as a brief description of the optimal short-term plan which is used as the basic input in our simulation model.

Chapter 4 presents the simulation results. The first part of the chapter considers determining the number of trucks using different scenarios. This part also describes the procedure of generating maintenance schedules for trucks. The second part assesses the performance of the designed truck-and-shovel system based on defined KPIs. In addition, this chapter presents an alternative scenario in which the possibility of sending material to stockpiles is considered. Finally, the last part verifies the simulation model and results.

Chapter 5 covers the contributions of this research and suggestions for future work.

CHAPTER 2

LITERATURE REVIEW

2.1 Open-pit Production Planning

Mineral deposits that are fairly near to the surface of the ground are best mined by open-pit mining, while deep-seated mineral deposits can be mined only by underground mining methods. Open-pit mining is mostly applicable to copper, iron, coal, and gravel deposits. The popularity and broad use of open-pit mining method is because of its high productivity, efficiency, and safety. Achieving such features requires a high capital investment that could reach several billion dollars.

Because of their size, significant capital investment, and decreasing grade of available deposits, open-pit mines require accurate planning and scheduling. Production scheduling is an important aspect of the mine planning and design process. Production scheduling is defined as making decisions about the extraction sequence of mine units, and the amount of ore and waste that should be sent to corresponding destinations such as processing plants, stockpiles, and waste dumps (Eivazy and Askari-Nasab, 2012).

Production planning is a continuous process throughout the life of a mine (LOM). Based on the duration of the planning horizon and the time span of each planning period, production planning is classified into two main categories (Hustrulid and Kuchta, 2006):

1. Long-term production planning
2. Short-term production planning

The duration of the long-term planning horizon is from 10 years up to the LOM. Each planning period usually has a time span of a year or two. Long-term planning evaluates the economic viability of the mine and generates an infrastructure for short-term planning. The main objective of long-term production planning is to get the highest profit from the mine over its life. This objective is usually addressed as maximizing the NPV. NPV is the sum of the discounted cash flows over the LOM. Critical parameters involved in long-term planning have a substantial impact on NPV. These parameters include ultimate pit limits, mine life, production rate, mining sequence, and cut-off grade. Inaccurately assessing these parameters may cause an incorrect judgment on the profitability of the mine.

The short-term planning horizon lasts from one year to a few years. Each planning period usually has a time span of one month to a few months. Long-term plans are used as the basis for short-term production planning. The main objective of short-term production planning is to meet the production target that was determined in the long-term plans. Short-term production planning's goal is to minimize the operational costs, while considering constraints similar to those considered in long-term planning. The outcome of short-term plans should not deviate from the long-term plans. The most critical parameters involved in short-term planning are mining capacity, stripping ratio, processing capacities, and feed grades (Eivazy and Askari-Nasab, 2012).

In short, the objective of mine production scheduling is to maximize NPV in long-term planning and to minimize deviations from the production target in short-term planning. Achieving either of these objectives is a difficult task because the problem is extremely complex. The source of this complexity is the vast number of parameters and resulting interactions involved in the problem. In recent years, the most commonly solution to the mine-production scheduling problem has been a mathematical programming approach. This approach was primarily addressed using pure integer programming by Johnson (1969), and further studied using different methods such as mixed integer programming (MIP), dynamic programming, and meta-heuristic techniques such as Lagrangian relaxation (Osanloo et al., 2008). Most of the research in this area is for long-term rather than short-term production scheduling (Eivazy and Askari-Nasab, 2012).

In this research the optimal short-term production schedule developed by Eivazy and Askari-Nasab (2012) is used as the major input to the simulation model. They applied a mathematical programming approach to develop a MILP model to solve the short-term production scheduling problem. The generated production plan defines the monthly production requirements of an open-pit mine for a time horizon of one year. The extraction sequences of mining units (mining-cuts) as an output of production planning are the input into the simulation model.

2.2 Simulation in Mining Industry

Over the last two or three decades, simulation has been one the most admired OR tools. The main reason for this popularity is that simulation is able to deal with complex models and, thus, to represent complex systems. Also, owing to improvements in computer performance and price, simulation has become more cost effective. Finally, simulation is attractive because it is flexible, powerful, and easy to use (Kelton et al., 2007).

Simulation has been used in both open-pit and underground mines throughout the world. This approach is mostly applied in material-handling-and-haulage systems, mining operations, mine planning, and production scheduling (Yuriy and Vayenas, 2008). There is an increasing interest in simulation applications in mining, especially in the Canadian mining industry. Simulation techniques are applied in Canadian mines mostly in the following trends (Vagenas, 1999):

- To create three-dimensional animation to visualize entire ore bodies;
- To perform reliability assessments of mining equipment;
- To assist in real-time mine management and in integration with spatial databases;
- To develop both strategic and tactical mine planning to provide insight to long-term and short-term requirements.

The very first mine simulation studies date back to the 1950s. Based on the nature of mine operations, simulation studies in a mining context are classified into two main groups: (1) underground simulation studies and (2) open-pit simulation studies (Raj et al., 2009). Although simulation studies are carried out for both underground and open-pit mines, it seems that most of these simulation studies are done in open-pit mines (Hartman and Mutmansky, 2002; Raj et al., 2009).

Underground mines vary in size and complexity. They range from simple designed small mines with a production capacity of 100 tonnes per day, to very large complex mechanized mines with a production capacity of 100,000 tonnes per day. In an underground mine, a variety of equipment operates in different locations. Each piece of equipment has to work in accordance with the other. The simulation of such large and complex mines is a challenging issue.

Underground simulation studies are classified into three subcategories as (1) simulation of a material handling system, (2) simulation of stoping operations, and (3) simulation of a complete mine (Raj et al., 2009). Based on the size and level of mechanization, an underground mine can use a range of handling systems for ore and waste. As the material handling system becomes more complex, simulation becomes a more effective tool to study the system's behavior. Also, alternative working scenarios can be studied for the stoping operations in highly mechanized underground mines.

Nowadays, open-pit mines are extremely large and highly mechanized and they have a huge variety of earth-moving machinery. Effective utilization of the equipment requires planning, developing, and operating an accurate mine planning system, which can be done best by simulation techniques. A simulation model can optimize the system by evaluating alternative feasible operating scenarios (Raj et al., 2009).

Open-pit simulation studies are classified into four subcategories: (1) simulation of bucket-wheel excavator and dragline systems, (2) simulation of truck-and-shovel systems, (3) simulation of complete mine, and (4) simulation of other mixed systems. Figure 2 shows how simulation studies are classified in the mining industry.

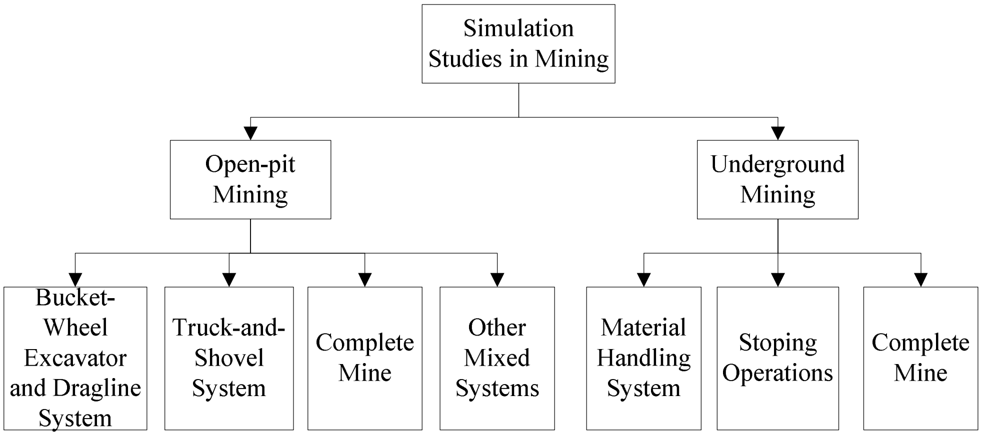

Figure 2. Classification of simulation studies in the mining industry

Typically, simulation models are classified as static vs. dynamic, continuous vs. discrete, and deterministic vs. stochastic. Discrete-event simulation is used to model complex systems such as manufacturing, transportation, and service systems. Discrete-event simulation models imitate discrete-event systems at discrete points in time. As a system evolves, its state variables change at these points in time. In continuous simulation, state variables of the system are observed continuously at every point in time (Rossetti, 2009).

Actual capabilities of simulation techniques are completely recognized when they are used to study complicated systems that have stochastic natures. Although deterministic approaches are widely used throughout the mining industry, they have a number of inherent limitations that impact their accuracy at estimating a system’s performance. Simulation models can successfully handle a system’s stochastic nature. Simulation models enable the user to conduct numerical experiments to study a system in detail and understand its behavior under different conditions.

However, as with any other optimization tool, simulation has limitations. Establishing an accurate and high quality simulation model can be time consuming and may require comprehensive field studies. These factors increase the cost of using this approach. However, simulation models are extremely capable of uncovering unrecognized and valuable interactions between system entities.

This thesis studies the design and performance analysis of a truck-and-shovel system. A truck-and-shovel system is complicated due to the number of operations involved and the interactions between units working in the system. Truck-and-shovel systems are also stochastic due to the uncertainties and probabilistic variables associated with most operations of the equipment. Because of these characteristics, other OR methods such as mathematical programming can't represent the system accurately.

According to the aforementioned classification, the simulation model developed in this study is dynamic, discrete, and stochastic. The developed model is a discrete-event simulation model because the state of the truck-and-shovel system changes in discrete points in time. The proposed simulation model is developed in Arena (Rockwell Automation, 2010) simulation software. Arena is one of the popular simulation modeling tools, because it has a powerful and operative user base (Rossetti, 2009).

2.3 Truck-and-Shovel System Study Approaches

Different methods to study truck-and-shovel material-handling-and-haulage systems are reported in the literature. These methods can be classified into three main categories:

1. Mathematical programming
2. Simulation
3. Stochastic methods such as queuing theory and stochastic programming

The rest of this chapter summarizes the literature about each of the three aforementioned methods.

2.3.1 Mathematical Programming Methods

Although mathematical programming-based models have been developed for truck-and-shovel systems since the 1970s, most have shortcomings. They do not take into account the stochastic nature of the truck-and-shovel systems, the economic parameters, and the multi-time-period nature of the mining operations (Gurgur et al., 2011). In conventional linear programming (LP)-based approaches the uncertainty is heuristically accommodated in the model. This is done by increasing the number of available recourses over the optimal solution. In conventional LP, uncertain parameters are considered in constraints and these constraints are met 50% of time.

Although mathematical programming methods have limitations in handling the stochastic complex system, some literature does apply this method. In research that uses the mathematical programming approach, truck-and-shovel haulage systems are usually designed as integrated multi-stage systems. In this approach, the first stage is to allocate trucks considering production requirements, and the second is to implement the solutions from the first stage using a real-time dispatching system. The second stage can be done with or without considering a dispatcher's interaction.

In the past, the only methods used for truck allocation and the dispatching problem were heuristic methods. Since then, mines preferred to use more accurate methods such as mathematical programming or a combination of mathematical programming and heuristic methods. Heuristic methods generally do not consider the whole problem because they solve the problem by simplifying it, which in return gives a solution that is good but not necessarily optimal (Gurgur et al., 2011). This is because heuristic methods are based on logical or practical operating procedures rather than mathematical proofs. So, heuristic methods do not guarantee an optimum solution. On the other hand, because heuristic methods are easy to implement and do not require much computation, they are common in literature. Heuristic methods mostly deal with dispatching problems, because decisions in most of the dispatching systems are taken in real-time (Alarie and Gamache, 2002).

Nowadays the most common approach to modeling truck-and-shovel systems is to represent the allocation problem with a mathematical programming model and the dispatching problem with a heuristic or a simulation model (Ta et al., 2005).

Temeng et al. (1997) integrate a transportation algorithm with a goal programming model to formulate a real-time dispatching process. They consider both the production rate and the ore grade in the objective function. They use a goal programming model to optimize the total production. Considering different haul routes between a source and a destination, they select routes that have the shortest cycle time, to optimize production at each haul route. Then, shovels are assigned to haul routes to minimize each route’s cumulative deviation of production from the optimal target production. In the last stage, using the transportation model, trucks are assigned to the shovels to minimize the total waiting time for both.

Some other studies, including those by Yan and Lai (2007) and Yan et al. (2008), develop mathematical programming models to optimize truck dispatching systems that are similar to haulage-in-mining operations. They study the production scheduling and truck dispatching problems in the same framework. Their methodology was applied to a ready mixed concrete case in Taiwan.

Fioroni et al. (2008) use a simulation model and an optimization model to generate short-term planning schedules. They employ Arena simulation software and Lingo optimization software to create monthly schedules in an open-pit mine. The interaction between the simulation model and optimization model is created using Visual Basic for Applications (VBA). Interaction between two models happens when a specific event takes place, for example, when a simulation model starts to run, a mining area is exhausted, or a truck or shovel fails. In the Fioroni et al. (2008) model, the number of interactions between these two models depends on the number of mining-faces and their material content, and the availability of trucks and shovels. The optimization model initially allocates the shovels, and then schedules the trips for the trucks. The optimization model repeats this process each time the state of the system changes. Its objective is to minimize the shovel movements while satisfying production and grade targets. The simulation model captures randomness in the truck-and-shovel system.

Yuriy and Vayenas (2008) are other examples of researchers who combine the mathematical programming model with a simulation model. They combine a reliability assessment with a discrete-event simulation model, to perform maintenance analysis on mining equipment. The reliability model is developed using a genetic algorithm. It aims to calculate the time between failures for each fleet. The output of this model is the input to the simulation model. The simulation model imitates the operations in the mine to evaluate the effect of failures on production rate, and to estimate fleet availability and utilization.

Topal and Ramazan (2010) develop a MIP model to schedule a fixed fleet of trucks for a given operation. The objective is to minimize truck maintenance costs while considering constraints subject to production targets. The scheduling is done on a yearly basis over a multi-year time horizon. The optimum truck schedule is generated based on the total hours of truck usage, maintenance cost, and required operating hours. The method is applied on a large-scale gold mine. Authors suggest using the same method in other businesses which use equipment with high maintenance costs.

Another example of dealing with a truck-and-shovel system with a multi-stage approach is the work by Gurgur et al. (2011). They develop an LP model to optimize truck allocation in open-pit mining. This model is implemented in association with an MIP model which generates short-term scheduling plans. The MIP model optimizes the material movement by maximizing the NPV, and satisfies constraints such as block sequencing and blending criteria. In the second stage, the LP model allocates trucks and shovels to minimize the deviation of material movement from the targeted material movement. The LP model satisfies constraints such as availability of trucks and shovels, location of shovels, and road profile.

2.3.2 Simulation Methods

Although simulation is very popular in the mining industry, it has limitations. On one hand, mining systems are sophisticated and there is not enough technical expertise and capital to support simulation (Castillo and Cochran, 1987). On the other hand, especially when studying mining haulage systems such as truck-and-shovel systems, simulation seems to be the most popular and handy tool. This popularity is due to the fact that simulation models successfully handle uncertainties in truck-and-shovel operations. Other methods, such as mathematical programming, are not capable of considering a system's uncertainties and details.

Most of the literature that applies simulation techniques evaluates only the dispatching policies of the truck-and-shovel system. One of the early works in this context is by Castillo and Cochran (1987). They analyze a conventional truck-dispatching system in an open-pit copper mine. The numbers of trucks and shovels are known, and the fixed dispatch policy is used to assign trucks to shovels. A microcomputer simulation model is developed using SLAM II to compare the proposed dispatching algorithm to the existent one. The algorithm maximizes truck utilization, and gives the priority to ore shovels to maximize ore production.

Another example is the early research done by Sturgul and Eharrison (1987), who simulate three different dispatching cases from three real surface mines in Australia. In the first case, employing a dispatching system in a coal mine is considered. Using a dispatching system can increase production, but it imposes an extra cost. In the second case, a surface uranium mine is considered to select the correct number of trucks to optimize production. In this case, instead of a dispatching system, each truck is assigned to a specific shovel and always returns to the same shovel. In the third case, a coal mine is considered. The coal mine currently uses a dragline for overburden removal, and a conventional truck-and-shovel for coal haulage. A combination of truck-and-shovel and hopper-and-conveyor belt is studied as an alternative. The correct numbers of trucks as well as the size of the hoppers are determined.

In addition, Bonates and Lizotte (1988) introduce different dispatching policies including fixed dispatch, maximize trucks utilization, maximize shovels utilization, and match factor. Using FORTRAN programming language, Bonates and Lizotte (1988) develop a computer simulation model for open-pit mines. The model optimizes truck-and-shovel operations with different dispatching policies. The suggested system is semi-automated and tries to meet the long-term production objectives. Results show that the maximize trucks utilization policy consistently yields higher production. If grade control is required or the differences in travel times between the shovels are significant, this is not the best policy. Maximize shovels utilization policy and match factor policy cause all the working shovels to operate at the same rate, which is generally more desirable. Whether these policies are efficient depends significantly on the available number of trucks.

Dual material-handling-and-haulage systems can operate in an open-pit mine. This case is presented by Peng et al. (1988), who construct a simulation model for an iron ore mine in northeast China. Such a semi-continuous open-pit mine has two main sub-systems: (1) the discontinuous in-pit truck-and-shovel system and (2) the continuous belt-elevator system. A program called SCSMLT is developed to determine the optimum number and size of shovels to be used with each crusher; the optimum number of trucks to be assigned to each shovel-crusher system over a certain haul-return distance; the optimum size of a crusher to meet the stripping and plant preparation requirements; and the optimum size of a surge or storage bunker for a specific crusher and conveyor system. Briefly, the program tries to match various types of equipment. This paper studies the effect of using different-sized equipment on the production rate. This paper also assesses how using different amounts of equipment in a series affects the reliability of the continuous system.

Li (1990) discusses three problems of truck-and-shovel systems in the operational level of an open-pit mine with computer simulation: (1) haulage planning, (2) truck dispatching, and (3) equipment matching. Haulage planning, also referred as material flow planning, finds the quantity of ore or waste to be transported along each route in the network of haul routes. A LP model is developed to determine the flow of trucks between the loading and dumping points for the set of feasible routes. The objective is to minimize transportation efforts while satisfying the required stripping ratio and ore quality. Truck dispatching finds how trucks should be assigned to the shovels. A new dispatching rule, maximum inter-truck-time deviation, is used to select the best dispatching strategy. Equipment matching finds the quantity of trucks to be employed. The number of trucks is determined by minimizing the sum of the squares of inter-truck-time deviations through simulation.

Forsman et al. (1993) is an example of using a discrete-event simulation model to evaluate a truck-and-shovel system in a copper ore mine in northern Sweden. This model merges simulation and graphical animation with computer-aided design. Input data includes truck speed at loaded and empty conditions for different road segments, and probability density functions for truck capacity, loading times, dumping times, breakdowns, and shift times. The model compares three different dispatching strategies: (1) fixed dispatch, (2) maximize trucks utilization, and (3) maximize shovels utilization. Results show that the maximize shovels utilization policy results in the lowest total tonnage. The maximize trucks utilization policy results in the same total tonnage as the fixed dispatch policy, but the ore tonnage is lower. The model also makes decisions about installing an in-pit crusher, purchasing new trucks, and planning a route for efficient material transportation.

Gove and Morgan (1994) introduce a fleet production and cost (FPC) program, which is developed by Caterpillar, to assess truck-and-shovel matching choices. FPC models the mine material-handling-and-hauling system with a four-part cycle that consists of load, haul, dump and maneuver, and return. If all equipment operates at 100% efficiency, the perfect match point between a loader and a hauler would be the intersection of the loader's potential production and the hauler's potential production. Since 100% efficiency is unreachable, FPC defines three job efficiency factors to evaluate the system. These factors include matching and bunching, operator efficiency, and equipment availability. The authors show an example of using FPC to find the best match between a 992D loader and a fleet of 777C trucks on a given haul road. They evaluate the production for different numbers of trucks using each of aforementioned job efficiency factors separately. Then, taking into account the cost of production and also different types of trucks, FPC tries to find the best match.

Karami et al. (1996) propose a simulation model to study truck-and-shovel haulage systems in an open-pit mine using SLAM II. They only consider the truck transportation system that includes a specific number of trucks which are assigned to a specific number of shovels. Simulation is used to evaluate the operating performance and understand the behavior of the mine under different haulage system configurations.

Awuah-Offei et al. (2003) use a simulation technique to forecast the truck-and-shovel requirements for a typical hard rock auriferous mine over a four-year period. SIMAN is used to simulate a gold mine in South Africa. In the model, trucks are defined as entities. Other operations, such as the arrival of entities, loading, movement of entities, unloading, maneuvering, and queuing are defined as processes. They also consider the haul route profile, because as the mining progresses, the pit deepens, the pit floor narrows and the grade and length of the haul routes change. Representative data from the truck-and-shovel system are collected and the proper density functions are fitted. These data include excavator loading times, truck travel times, frequency of excavator breakdowns and downtimes, and production rates.

Wang et al. (2006) use simulation to evaluate their proposed new real-time dispatching technique for open-pit mines, which is under macroscopic control. In this method, actual truck flow rates are controlled to be close to object truck flow rates, which are given by truck flow optimization. The new technique has two parts: (1) macroscopic dispatching principle and (2) concrete dispatching principle. The method is compared with the DISPATCH system's dynamic programming method and the fixed dispatch method. Simulation results, in both normal production conditions and abnormal production conditions where failure of equipment is considered, prove the advantages of the proposed technique.

Burt and Caccetta (2007) use match factor to indicate the fleet of truck-and-shovel system's efficiency. Match factor is used to predict productivity and select the best fleet by matching the truck arrival rate to the shovel service rate. In the balance point, match factor takes the value of 1.0 which indicates that trucks are arriving at the shovel at the same rate as they are being loaded. A ratio greater than 1.0 represents that the trucks are arriving faster than they are being loaded. A ratio of less than 1.0 represents that the trucks are arriving slower than they are being loaded. What is expected in the first case is a queue of trucks, and in the second case, a queue of shovels. Burt and Caccetta (2007) propose the new match factor for three different cases: (1) a case in which only trucks are heterogonous, (2) a case in which only loading fleets are heterogeneous, and (3) a case in which both trucks and loading fleets are heterogonous. They include the queue and waiting times in the cycle times, so they define the truck cycle time as the time it takes for a truck to be loaded with material, travel to the dumpsite, dump the load, travel back to the loader and queue for the next load.

A comparison between the application of simulation and other OR methods is also reported in the literature. Chanda and Gardiner (2010) compare computer simulation's ability to estimate truck cycle time in open-pit mining with two other methods: artificial neural networks (NNs) and multiple regressions (MRs). In defining the truck cycle time, they consider only the truck travel time, which includes the truck's travel time when it is loaded and when it is empty. The comparison is based on the deviation from the actual truck cycle time, which is obtained by computerized monitoring of a fleet of trucks at a large open-pit gold mine in western Australia. They state that although computer simulation is the most common method for predicting truck cycle time, it usually overestimates or underestimates the cycle time. They prove that NNs and MRs estimate the truck cycle time more accurately than simulation software such as TALPAC.

2.3.3 Other Stochastic Methods

2.3.3.1 Queuing Theory

Queuing theory was primarily applied in the field of computer systems and computer communication networks. Some studies have applied queuing theory to analyze truck-and-shovel haulage systems in open-pit mining. The first application of queuing theory in a mining context was done by Koenigsberg (1958). He uses the cyclic queues approach to calculate the production for a specific number of crews performing conventional room-and-pillar mining activities at a known number of faces. He applied his method to a simple mine haulage system in Illinois. His work is later followed by that of Carmichael (1986; 1987).

Also, Kappas and Yegulalp (1991) apply queuing network theory to perform a steady state analysis on a generalized truck-and-shovel system in a typical open-pit mine. They model the truck-and-shovel system as a network in which trucks are customers and mining operations are completed at various service centers. They estimate the system’s critical performance parameters and compare them with simulation results that show an error of less than 5%.

Muduli and Yegulalp (1996) are another example of researchers who model the truck-and-shovel haulage system as a closed queuing network. They use mean value analysis to study the effect of choosing different types of trucks. Each type of truck has specific attributes. They evaluate the production level and other system performance measures

Queuing theory models usually try to determine the optimum number of trucks. For example, Czaplicki (1999) proposes a queuing theory-based procedure to assess the optimum number of operating and reserve trucks in a mine. Two types of truck-and-shovel systems are considered: (1) one shovel and a certain number of trucks and (2) a certain number of shovels and trucks. Czaplicki (1999) considers many important technical and stochastic properties of the system.

Another study that uses queuing theory is that of Trivedi et al. (1999) who use it to optimize the combination of trucks and shovels in an open-pit mine in India. They optimize the number of trucks by evaluating different scenarios with different numbers of trucks and the same number of shovels. Factors affecting the decision about the number of trucks to use include the length of queues, waiting time in queues, shovel use, production rate, and costs involved in the system.

Queuing theory can also be used to determine the required number of shovels. Alkass et al. (2003) develop a computer module, based on queuing theory, to help determine the size and number of trucks and excavators, haul road lengths, and surface conditions . The module provides a list of the best ten fleet alternatives in different haul routes. This approach deals with the uncertainties associated with the equipment selection. The method is applied on a real case and results are compared with results from simulation.

Krause and Musingwini (2007) modify the machine-repair model to estimate the size of a truck fleet in an open-pit mine that uses a truck-and-shovel haulage system. The machine-repair model emulates a system that consists of a finite number of machines and a finite number of repair bays. The proposed method is applied on a virtual case and a real open-pit coal mine. A simulation model is developed in Arena and chosen as a benchmark. Results from the Arena model are compared to those from simulation packages such as TALPAC and FTP.

The queuing theory method can also be combined with other methodologies. Ercelebi and Bascetin (2009) present a two-stage procedure to study a truck-and-shovel system. In the first stage, a model based on the closed queuing network theory proposed by Muduli and Yegulalp (1996) is used to determine the optimal number of operating trucks. In the second stage, a LP model is used to specify the dispatching sequence of trucks to shovels. Ercelebi and Bascetin (2009) apply the proposed method on an open-pit coal mine in Turkey to evaluate the accuracy of the method in measuring the system's performance indicators. These performance indicators include mine throughput, number of trucks, and waiting times.

Queuing theory can be the basis for a model developed in other methods. Ta et al. (2010) develop an optimization-based truck allocation model, which relies on queuing theory. In their model, a finite number of trucks is assigned to each shovel. They assume trucks are customers and shovels are servers. They propose an approximate formula based on queuing theory to quantify the nonlinear relationship between the number of trucks assigned to a shovel and the shovel's throughput. Linearization is used to embody this formula in linear integer programming. The objective is to minimize the number of trucks assigned to a set of shovels while considering throughput and ore grade constraints.

2.3.3.2 Stochastic Programming

There is a limited amount of literature on stochastic programming applied in the field of mining. It seems that the only literature that uses stochastic programming directly in evaluating a truck-and-shovel system is that by Ta et al. (2005).

Ta et al. (2005) propose a truck allocation model which is based on two uncertain parameters: (1) truck cycle time, and (2) truck load. The objective of the model is to minimize ore delivery's operating and capital costs. This objective is formulated as minimizing the required number of trucks to satisfy the production demand. In the first stage, Ta et al. (2005) use recourse-based stochastic programming and define a chance-constrained truck allocation problem to improve initial truck allocation. Solutions at this stage are implemented in real-time hauling framework to determine the density function of uncertain parameters. Next, these density functions are used as feedback data, and subsequent truck reallocations are done. A custom discrete-event simulator is developed to implement the approach on a mine with a simplified haulage configuration. Two scenarios, one with and the other without upsets, are studied.

2.4 Summary and Remarks

Chapter 2 has presented a review of the relevant literature. Clearly, the ability to accurately assess a truck-and-shovel system's performance in an open-pit mine is very important for mining companies. Any marginal improvement in the system's performance would save a significant amount of money. In most modern open-pit mining operations, very large capital investments are required to purchase and replace the necessary equipment. An accurate performance assessment is not an easy task. This is because a truck-and-shovel system is complex as a result of its stochastic features and significant number of interactions between elements.

This chapter contains explanations of three different methodologies used to evaluate truck-and-shovel systems: (1) mathematical programming, (2) simulation, and (3) other stochastic methods such as queuing theory. Among these methods, simulation seems to be the most powerful in terms of handling the uncertainties associated with truck-and-shovel systems. Mathematical programming methods such as LP usually cannot deal with the uncertainties associated with the operations of trucks and shovels. Because of these drawbacks, mathematical programming models are usually combined with simulation models or other stochastic approaches. However, there is very little in the literature about using mathematical programming in regards to uncertainties about truck-and-shovel systems. Queuing theory and stochastic programming have the capability to consider stochastic variables (Alkass et al., 2003). In stochastic programming, the uncertainty is explicitly included in the numerical solution. Constraints can be satisfied by an explicitly expressed confidence (Ta et al., 2005). Queuing theory requires highly complex mathematical formulations. So, the number of simplifying assumptions in this method is significant. In conclusion, none of these methods can directly embody the uncertainties in the model.

Model development using any method needs some simplifying assumptions. The assumptions also include the decision about the boundaries of the system which is being studied. One should decide to study the truck-and-shovel system alone or to consider other operations in the system as well, such as operations involved in processing plants. The amount of the assumptions is related to the available time and money. Fairly accurate results can be obtained using computer simulation techniques, with some simplifying assumptions. In current literature about truck-and-shovel models, few details are covered. Considering more details makes the models complicated, which means that more time, money, and computer memory are needed to find a solution.

Another shortcoming in the current literature, especially in that which uses e mathematical programming, is that it models the truck-and-shovel system based on the shovel's production requirements. With this approach shovels are assumed to work continuously. Almost no literature tries to study the concurrent movement of shovels and trucks.

The smallest unit of mining material in existent truck-and-shovel models in literature is mining-zone or mining-face. These models assume that each zone is a single uniform unit that has a single grade for each element, and single tonnage characteristics. This imposes the assumption that all blocks in a mining-zone are identical and there is no extraction sequence between mining-blocks. But in reality the smallest mining units are mining blocks which have distinct ore and waste percentages and distinguished grades of elements.

Finally, a huge portion of research focuses on the truck-and-shovel system as a closed system. Almost no research considers the interactions with other systems, such as processing systems, in the mine. Very little research takes into account the activities and uncertainties of these systems' operations.

In summary, the main shortcomings of the current research on truck-and-shovel systems in open-pit mining are:

- The stochastic nature of the truck-and-shovel system is ignored;
- Only a limited amount of details can be considered in the model;
- The system is modeled based on the shovel's production requirements and assumes that shovels are continuously working;

- The characteristics of each mining-block and the block extraction sequences are ignored.
- The interactions between the truck-and-shovel system and other systems involved in mining operations are limited.

To a certain extent, the research in this thesis overcomes these drawbacks:

- Regarding the first drawback, because the simulation technique is applied in this study, stochastic variables of truck-and-shovel systems can be considered in the model. These uncertainties include truck velocity during day and night shifts, shovel velocity, shovel's bucket capacity, dump time, and failures of fleets and facilities.
- Regarding the second limitation, the developed model represents a truck-and-shovel system with near-sufficient details. Considering more of the system's details requires more time and computational memory.
- Regarding the third shortcoming, the system's design and performance analysis is implemented based on the short-term mine plan, which is derived from overall mine plan requirements according to the economic and operational objectives. This approach guarantees that the designed truck-and-shovel system's operations will honor mine planning's main objective.
- Regarding the fourth weakness, since the simulation model is linked to the short-term plans, a mining unit which is smaller than a mining-zone or a mining-face is defined. The mining-cut is defined as a mining unit with distinct location, tonnage, and grades. This approach also takes into account the precedence between mining-cuts, which is another important contribution of this research.
- Finally, the simulation model also considers the crushers as units that interact with the truck-and-shovel system. The proposed model includes sub-models representing the reclamation process. Also, an alternative scenario for the current mining operations is considered in this study. The

scenario is to send the material to stockpiles when a crusher is broken down.

CHAPTER 3

THEORETICAL MODELS

This chapter deals with two different approaches to a truck-and-shovel material-handling-and-haulage system in open-pit mining operations. In the first approach, which is a mathematical programming approach, a MILP model is developed. The MILP formulation deals with the allocation problem in which trucks and shovels are assigned to mining-faces.

In the second approach, a simulation model is developed to integrate the optimal short-term plan with truck-and-shovel operations. The model determines the required numbers of trucks and shovels, generates a maintenance schedule for trucks, further analyzes the performance of the system by assessing KPIs, and tries to improve the system. The model takes into account the characteristics of the mine's material content in mining-cut resolution, and considers the extraction sequence between mining-cuts. Also, the uncertainties associated with the truck-and-shovel operations are taken into consideration in the simulation model.

Details of each proposed model are explained in the following sections.

3.1 Mathematical Programming Model

3.1.1 Allocation Problem

Resource allocation problems are central to many real-world planning problems, including load density function, production planning, computer scheduling, portfolio selection, etc. They also emerge as sub-problems of more complex problems. The resource allocation problem determines how a fixed amount of resources is allocated to various activities, in order to optimize the objective function under consideration.

In the mining context, resource allocation may refer to the allocation of trucks and shovels to mining-faces. Many mining companies try to allocate trucks and shovels to mining-faces so that the operating costs are minimized and resource utilizations are maximized through the planning horizon.

In mining operations, trucks and shovels are used as resources in extraction and haulage operations. Shovels are used to extract the material and load it to the trucks. Trucks operate continuously to haul the material to various destinations to further process as ore, or to dump as waste.

The numbers and types of trucks and shovels are important parameters in optimal design of open-pit mine material-handling-and-haulage systems. The truck-and-shovel allocation problem involves determining the numbers and sizes of trucks and shovels, and how they will match up. Truck and shovel availability, useful economic life, spare parts availability, and maintenance and operating costs are factors affecting the types of trucks and shovels chosen for extraction and haulage activities.

This chapter deals with the allocation problem in the context of mining operations with the focus on the truck-and-shovel material-handling-and-haulage system. The goal is to allocate the resources, which are trucks and shovels, to mining-faces over a shift. For this purpose, MILP model is proposed.

The following assumptions are the basis of the mathematical programming model developed for the truck-and-shovel allocation problem. An open-pit mine consisting of different mining-faces is taken into account. There are two fixed destinations for the trucks: a crusher and a waste dump. It is assumed that shovels and trucks of different types with different sizes are available. Each type of truck has a specific size and hauls a different volume of material. Due to failures and scheduled maintenance, the number of available trucks of each type and available shovels may vary from one period to another.

At the beginning of each period, a decision is made about assigning trucks and shovels to the mining-faces which are ready to be extracted. The type of the material at each mining-face specifies each truck’s destination. If the material type is ore, assigned trucks go to the crusher. If it is waste, they go to the waste dump. The number of trips of each type of truck takes to different destinations is another variable to be decided in the model. This assignment must be done in such a manner as to ensure that loading and haulage costs are minimized.

The grades of different minerals and metals directly affect mining costs. The model considers grades of materials in the mining-faces. Shovels and trucks are allocated to the mining-faces to meet the blending constraints at the crusher. Any deviation from the target production at the crusher results in a penalty, which translates to extra costs. In addition there are costs associated with the trips that trucks take from a mining-face to different destinations. The cost of a shovel travelling from its location to a new mining-face location is also considered. Other assumptions considered in building the MILP model are as follows:

- Each mining-face is available to be extracted at specific periods;
- There is a maximum and minimum limit on the crusher's production capacity;
- Specific types of trucks can work with specific types of shovels;
- The number of available trucks of each type is known at the beginning of the period;
- The number of available shovels is known at the beginning of the period;
- Maximum and minimum production capacity of shovels and load capacity of trucks are known;
- A truck's capacity, in terms of tonnes, depends on the type of material it is hauling;
- Only one shovel operates at each mining-face at a time;
- Each shovel can operate at only one mining-face at a time;
- The time horizon for the model is an eight-hour shift.

3.1.2 MILP Formulation

Sets

$I = \{1,...,I\}$	Set of mining-faces.
$J = \{1,...,J\}$	Set of shovels.
$K = \{1,...,K\}$	Set of types of trucks.

Indices

$i \in I$	Index for mining-faces.
$j \in J$	Index for shovels.
$k \in K$	Index for types of trucks.

Parameters

$MAT_i \in \{0,1\}$	Current material type of mining-face *i*. It is equal to 1 if current material type of mining-face *i* is ore; otherwise it is equal 0.
ORE_i	Remaining ore tonnage at mining-face *i* (tonnes).
$WASTE_i$	Remaining waste tonnage at mining-face *i* (tonnes).
$AVL_i^{face} \in \{0,1\}$	Availability of mining-face *i*. It is equal to 1 if mining-face *i* is available; otherwise it is equal to 0.
$AVL_j^{shovel} \in \{0,1\}$	Availability of shovel *j*. It is equal to 1 if shovel *j* is available; otherwise it is equal to 0.
$SHCAP_j^{\max}$	Maximum production capacity of shovel *j* (tonnes per hour).

$SHCAP_j^{\min}$	Minimum production capacity of shovel *j* (tonnes per hour).
NUM_k	Number of available trucks of type *k*.
$COMP_{jk} \in \{0,1\}$	Compatibility of truck *k* with shovel *j*. It is equal to 1 if truck *k* is compatible with shovel *j*; otherwise it is equal to 0.
CT_{ik}^{ore}	Cycle time of truck type *k* transferring ore from mining-face *i* to the crusher (seconds).
CT_{ik}^{waste}	Cycle time of truck type *k* transferring waste from mining-face *i* to the waste dump (seconds).
CAP_k^{ore}	Capacity of truck type *k* when transferring ore (tonnes).
CAP_k^{waste}	Capacity of truck type *k* when transferring waste (tonnes).
GR_{il}	Grade of element *l* at mining-face *i* (%).
UB_l	Upper bound of grade blending for element *l* (%).
LB_l	Lower bound of grade blending for element *l* (%).
$PMAX$	Maximum processing capacity of the crusher (tonnes).
$PMIN$	Minimum processing capacity of the crusher (tonnes).
MC_{ij}	Trip cost of shovel *j* travelling from its current location to mining-face *i* ($).
TRC_{ik}^{ore}	Trip cost of truck type *k* travelling from mining-face *i* to the crusher ($).
TRC_{ik}^{waste}	Trip cost of truck type *k* travelling from mining-face *i* to the waste dump ($).

DC	Cost of deviation from target production ($ per ton).
T	Planning time duration (hours).

Decision Variables

$a_{ij} \in \{0,1\}$	Binary integer decision variable representing assigning of shovel *j* to mining-face *i*. It is equal to 1 if shovel *j* is assigned to mining-face *i*; otherwise it is equal to 0.
n_{ik}^{ore}	Continuous decision variable representing number of trips of truck type *k* from mining-face *i* to the crusher.
n_{ik}^{waste}	Continuous decision variable representing number of trips of truck type *k* from mining-face *i* to the waste dump.
x_i	Extracted material tonnage from mining-face *i* (tonnes).

Objective Function

$$\begin{aligned} \text{Minimize } Z = & \\ & \sum_{i \in I} \sum_{j \in J} MC_{ij} \cdot a_{ij} \\ & + \sum_{i \in I} \sum_{k \in K} (TRC_{ik}^{ore} \cdot n_{ik}^{ore} + TRC_{ik}^{waste} \cdot n_{ik}^{waste}) \\ & + DC \cdot (PMAX - \sum_{i \in I} MAT_i \cdot x_i) \end{aligned} \tag{3.1}$$

Constraints

$$\sum_{j \in J} a_{ij} \le AVL_i^{face} \qquad \forall i \in I \tag{3.2}$$

$$\sum_{i \in I} a_{ij} \le AVL_j^{shovel} \qquad \forall j \in J \tag{3.3}$$

$$CT_{ik}^{ore} \cdot n_{ik}^{ore} \le 3600 \cdot T \cdot NUM_k \cdot MAT_i \qquad \forall i \in I, k \in K \tag{3.4}$$

$$CT_{ik}^{waste} \cdot n_{ik}^{waste} \leq 3600 \cdot T \cdot NUM_k \cdot (1 - MAT_i) \qquad \forall i \in I, k \in K \tag{3.5}$$

$$n_{ik}^{ore} \leq \sum_{j \in J} a_{ij} \cdot COMP_{jk} \qquad \forall i \in I, k \in K \tag{3.6}$$

$$n_{ik}^{waste} \leq \sum_{j \in J} a_{ij} \cdot COMP_{jk} \qquad \forall i \in I, k \in K \tag{3.7}$$

$$\sum_{i \in I} n_{ik}^{ore} \cdot CT_{ik}^{ore} + \sum_{i \in I} n_{ik}^{waste} \cdot CT_{ik}^{waste} \leq 3600 \cdot T \cdot NUM_k \qquad \forall k \in K \tag{3.8}$$

$$x_i \leq \sum_{j \in J} T \cdot SHCAP_j^{\max} . a_{ij} \qquad \forall i \in I \tag{3.9}$$

$$x_i \geq \sum_{j \in J} T \cdot SHCAP_j^{\min} . a_{ij} \qquad \forall i \in I \tag{3.10}$$

$$\sum_{i \in i} x_i \cdot MAT_i \leq PMAX \tag{3.11}$$

$$\sum_{i \in i} x_i \cdot MAT_i \geq PMIN \tag{3.12}$$

$$x_i \cdot MAT_i \leq ORE_i \qquad \forall i \in I \tag{3.13}$$

$$x_i \cdot \left(1 - MAT_i\right) \leq WASTE_i \qquad \forall i \in I \tag{3.14}$$

$$x_i = \sum_{k \in K} CAP_{ik}^{ore} \cdot n_{ik}^{ore} + \sum_{k \in K} CAP_{ik}^{waste} \cdot n_{ik}^{waste} \qquad \forall i \in I \tag{3.15}$$

$$\sum_{i \in I} GR_{il} \cdot x_i \leq \sum_{i \in I} UB_l \cdot x_i \qquad \forall l \in L \tag{3.16}$$

$$\sum_{i \in I} GR_{il} \cdot x_i \geq \sum_{i \in I} LB_l \cdot x_i \qquad \forall l \in L \tag{3.17}$$

$$a_{ij} \in \{0,1\} \qquad \forall i \in I, j \in J \tag{3.18}$$

$$n_{ik}^{ore}, n_{ik}^{waste} \in Z \qquad \forall i \in I, k \in K \tag{3.19}$$

$$x_i \geq 0 \qquad \forall i \in I \tag{3.20}$$

In the developed MILP formulation, the objective function tries to minimize the costs associated with truck-and-shovel operations. The first term in Equation (3.1) is the total cost of shovels travelling to new mining-faces. The second term is the total transportation cost of trucks travelling to the waste dump or to the crusher. The last term in Equation (3.1) is the cost of negative deviation from the production target at the crusher.

Equation (3.2) indicates that at each available mining-face only one shovel can operate, and if a mining-face is not available, no shovel should be assigned to that mining-face. Equation (3.3) assures that each available shovel can operate at only one mining-face.

Equation (3.4) limits the number of trips for a fleet of trucks travelling from each mining-face to the crusher. Equation (3.5) restricts the number of trips for a fleet of trucks travelling from each mining-face to the waste dump.

Equation(3.6) and Equation (3.7) guarantee that a truck could travel to a mining-face only if a shovel is assigned to that mining-face and the shovel is compatible with that type of truck.

Equation(3.8) denotes that the total number of trips that each truck type makes to the crusher or to the waste dump is less than the maximum possible trips of that truck type.

Equation(3.9) and Equation (3.10) ensure that the production of each mining-face is between the minimum and maximum possible production of the shovel assigned to that mining-face.

Equation(3.11) and Equation (3.12) aim to meet the crusher's limits of processing capacity. Equation(3.13) and Equation (3.14) force each mining-face to produce less than the maximum amount of available material.

Equation (3.15) defines the production of each mining-face based on the number of trips made by each fleet of trucks. Equation(3.16) and Equation(3.17) ensure that the grade blending at the crusher is between specified upper and lower limits. Equation (3.18), Equation (3.19), and Equation (3.20) define types of different decision variables.

Solving the MILP model with an optimization tool and integrating it with a simulation model is recommended for future research.

3.2 Simulation Model

3.2.1 Truck-and-shovel System Specifications

This thesis studies the simulation modeling of truck-and-shovel operations in open-pit mining with a direct linkage to an optimal short-term production plan. The optimal short-term production schedule generated by Eivazy and Askari-Nasab (2012) is the basic input to the simulation model. In the short-term plan generated by these researchers, blocks are aggregated into practical scheduling units which are referred to as mining-cuts. The short-term schedule determines the extraction plan of mining-cuts in a time horizon of one year, and it consists of 12 production periods.

The short-term plan provides information about the number and IDs of mining-cuts that should be extracted at each period. Also, the following information is available in the short-term plan for each of the mining-cuts:

- Precedent mining-cuts that should be extracted before each mining-cut;
- Coordinates of the mining-cuts' location;
- Material content of the mining-cut which is defined as ore tonnage and waste tonnage;
- Grades of different elements, which include phosphor, sulfur, and magnetic iron;
- Periods during which the mining-cut is extracted;

- Destinations where the mining-cut's content material should be delivered;
- The portion of the mining-cut that should be extracted at each period and delivered to a specific destination; and
- The number and length of the ramp through which the material is hauled to the pit-exit point.

The open-pit mine has a large pit consisting of mining-blocks. For this pit, a unique pit-exit has been designed. There are six different destinations in the mine: two waste dumps, two stockpiles, and two processing plants. The main element of interest in the deposit is iron. Phosphor and sulfur are considered as contaminants to be controlled. It is assumed that stockpile 1 feeds only crusher 1 and stockpile 2 feeds only crusher 2. The information about the tonnage and grade of material reclaimed from each stockpile at each period is also determined in short-term production schedule.

A typical truck-and-shovel system is considered, in which shovels extract material and load them to the trucks. Trucks haul material from inside the pit to the pit-exit point through different ramps. Then, they travel from pit-exit point to the final destinations. When a truck is loaded it has a different average velocity compared to the average velocity when the truck is unloaded. Also, a truck has different average velocities during day and night shifts.

In detail, the process is as follows: based on the information about each period, a shovel travels to the location of a mining-cut which is available to be extracted. It takes some time for the shovel to travel from its current location to the mining-cut's location. Simultaneously, a truck travels from its current location to the same mining-cut location as the shovel. The shovel starts its work to extract a portion of the mining-cut and load it into the truck. The truck stays by the working shovel until it is fully loaded. If the material type of a truck's load is ore, it will be delivered to a stockpile or a processing plant. If it is waste, it will be delivered to one of the waste dumps. Classification of material as ore, stockpile, and waste material, as well as the material's respective destination, is based on the optimal short-term schedule. At the same time, another truck travels to the shovel to be loaded. The shovel moves to another mining-cut's location right after the current mining-cut is completely depleted.

Trucks unload at the predetermined destination and travel back to the pit-exit point. There is limited space available for trucks to dump at one destination, either at a waste dump or a stockpile or a processing plant. Regarding the rehandling process, a loader and a truck are used to reclaim material from stockpiles. In the simulation model, trucks, shovels, waste dumps, stockpiles, and crushers are modeled as resources of the truck-and-shovel operations.

This study considers the uncertainty in truck-and-shovel operations. The uncertainty is captured by using the following random variables in the discrete-event-simulation model:

- The tonnage that a shovel can extract at each load-pass;
- The time that it takes to complete one load-pass;
- The time that it takes to dump a load at a destination;
- Moving velocity of a shovel;
- Velocity of a truck when it is loaded and when it is unloaded during day and night shifts;
- Mean time between failures (MTBF) and mean time to repair (MTTR) for truck minor and major failures;
- MTBF and MTTR for shovel failure; and
- MTBF and MTTR for crusher failure.

The failures of trucks, shovels, and crushers are defined with uncertain up-times and down-times. MTBF is the time interval between two failures, and MTTR is the duration of the failure. All random variables are represented by probability density functions. Most of the probability density functions are obtained by performing data analysis on historical dispatching data gathered from a Jigsaw dispatching database. To fit the suitable probability density function, Arena Input Analyzer (Rockwell Automation, 2010) is used.

3.2.2 Analysis Procedure

The problem of modeling and analyzing the truck-and-shovel material-handling-and-haulage system in an open-pit mine is divided into two sub-problems. In the first sub-problem, the equipment selection problem is considered. In the simulation model, trucks and shovels are modeled as main resources of the truck-and-shovel operations, of which the use is very important. Also, waste dumps, stockpiles, and crushers are considered as resources. In this study, it is assumed that all trucks and all shovels are identical. This means that characteristics of trucks and shovels, such as types and sizes, are the same. With this assumption, the equipment selection problem is reduced to determining only the numbers of trucks and shovels to be employed.

To determine the required number of resources, different scenarios with different numbers of trucks and shovels are generated. For this purpose, Arena Process Analyzer (Rockwell Automation, 2010) is used. In the initial scenario, a small numbers of trucks and shovels are considered. Then, the numbers of trucks and shovels are increased continually in the subsequent scenarios.

The dominant criterion used to evaluate each scenario is the production target for the whole planning horizon. The production target is determined by the short-term production schedule. With this approach, scenarios in which the production target is met are considered feasible. To choose the best scenario among feasible ones, other criteria are used. Those criteria include average shovel use and average truck use. In short, the best scenario is one that meets the production target and results in the highest utilization of trucks and shovels. The actual truck-and-shovel system uses the amount of trucks and shovels determined by the best feasible scenario.

The aforementioned procedure is implemented under different assumptions. First, it is assumed that none of the trucks, shovels or crushers fails at anytime. With this assumption the required numbers of resources are chosen. Then, the procedure is repeated for the situation where possible failures of resources can occur. At this stage, the average use of trucks and shovels is assessed during each period, not the whole planning horizon.

Because of stochastic variables in the model, some variations in the use of trucks or shovels may be seen from one period to another. In such cases, scenarios should be reassessed. The purpose of this phase is to employ fewer trucks or shovels during some periods, to increase the use of the available resource in those periods. As a result, a maintenance schedule is generated, showing how many trucks or shovels are unavailable, and when, due to planned maintenance. This phase is important because it makes it possible to not use unnecessary equipment . With a maintenance schedule, the mine can save money because there is less wear-and-tear on equipment, and the people responsible for the equipment can be assigned to other tasks.

The chosen numbers of trucks and shovels is used as a resource in the simulation model, and further analysis on the system's KPIs is done in the second sub-problem. Most of the KPIs are evaluated for a time span of a month. Some are further assessed during day and night shifts. This study deals with the following KPIs:

- Total delivered material tonnage. This KPI is the most critical criterion in the first sub-problem, and it is also very important in verifying the simulation model. It is assessed in time spans of both a month and a shift. Total delivered material tonnage should not deviate from monthly production targets.
- Average truck utilization and average shovel utilization. These KPIs are used in both first and second sub-problems. They are the main measure for the system's performance and show the percentage of time that the resources are used.
- Average grades of elements such as phosphor, sulfur, and magnetic iron. These KPIs are defined as weighted averages. For example, the mixture of load l_1 and l_2 has an average grade of an element which is calculated as:

$$\frac{\left(weight\ of\ load\ l_1\ .\ grade\ of\ load\ l_1\right)+\left(weight\ of\ load\ l_2\ .\ grade\ of\ load\ l_2\right)}{weight\ of\ load\ l_1+weight\ of\ load\ l_2}$$

- Average truck waiting time. This KPI is evaluated during each period and also during day and night shifts. Trucks usually wait in a queue for a resource to become available. When a resource is not available, it could be because it is already busy or has failed. Average truck waiting time is an important KPI which this study tries to improve in the next phase.
- Average truck queue lengths. As the truck waiting time increases, the queue length increases.
- Average truck cycle time. In this study, the truck cycle time is defined as the sum of the times that it takes a truck to travel from the pit-exit point to the mining-cut's location, be loaded by the shovel, travel to the destination, dump, and travel back to pit-exit point. This KPI is very important in verifying the simulation model.

Among these KPIs, this study tries to reduce the truck waiting time, if possible. Any improvement in truck waiting time would impact the truck queue length and truck cycle time and, thus, improve the system's total efficiency. As mentioned before, a truck waits for a resource because the resource is either busy or has failed. Crushers are one of the resources that face failures. The largest contributor to the truck waiting time is the crusher failures.

In this stage of the study, some new assumptions are introduced in the model. It is assumed that if a crusher has failed, no trucks will travel to that processing plant. Instead, trucks are redirected to the corresponding stockpile. A truck can face crusher failure either when it is leaving the pit-exit point or is on its way to the crusher. So, the decision about sending a truck to a stockpile because of crusher failure is made in two different points in time: (1) before leaving the pit-exit point and (2) at the crusher.

With this approach, the content of stockpile at each period is sourced from two different flows of material. One is a planned flow of material which is based on the short-term production schedule. The other is the material flow which was supposed to go to the processing plant, but is delivered to the stockpile, because of the crusher's failure. The latter material flow is referred as unplanned flow of material.

Thus, in addition to scheduled reclamation from stockpiles, extra reclamation should be done to meet the production target. Reclaiming the unplanned flow of material from each period is done during the subsequent period. During the reclamation process, stockpile 1 feeds crusher 1 and stockpile 2 feeds processing plant 2. Because of this, trucks facing a failure of crusher 1 would deliver the material to stockpile 1, and trucks facing a failure of crusher 2 would deliver the material to stockpile 2.

3.2.3 Pseudo Codes and Flowcharts

This section describes the steps involved in the simulation model. Step 1 to Step 54 explains the main simulation model that deals with the extraction and haulage operations. Step 55 to Step 72 explain the sub-model that deals with the reclamation process. The last part of this section represents the modifications made to these two models to improve average truck waiting time.

3.2.3.1 Main Model

Step 1 Define main entities in the model (*ent block*). A main entity is a portion of a mining-cut that will be extracted at a specific period and will be delivered to a specific destination.

Step 2 Increase the global variable counting mining-cuts (*v block number*) by one unit.

Step 3 Assign the main entity's number (*a block number*) equal to the *v block number*. The main entity's number is its identification number (ID) in the simulation model.

Step 4 Assign attributes of the mining-cut. Some of these attributes are determined directly by the optimal short-term schedule, and include:

- The mining-cut's ID used in the optimal short-term schedule (*a id*)
- The period number in which it should be extracted (*a period*);
- Coordinates of the mining-cut's location (*a x*, *a y*, and *a z*);
- The mining-cut's tonnage (*a block ton*);
- The portion of the mining-cut to be extracted at a specific period (*a fraction*);
- The mining-cut's corresponding destination where its material should be delivered (*a destination*);
- Grades of sulfur, phosphor, and magnetic iron (*a p*, *a s*, and *a mwt*);
- The distance from the mining-cut's location to the pit-exit point (*a dis exit*);
- The distance from mining-cut's location to the corresponding destination (*a dis destination*);
- IDs of the precedent mining-cuts which should be completely depleted before the mining-cut (*a precedence 1*, *a precedence 2*, …, *a precedence 11*). Based on the short-term schedule, a mining-cut could have 11 or fewer precedent mining-cuts.

Some other attributes should be calculated. These attributes include:

- The entity's total tonnage (*a entity ton*) which is equal to a portion of the mining-cut that should be extracted at a specific period and be delivered to a specific destination. This attribute is calculated as $a\ block\ ton \times a\ fraction$;
- Its remaining tonnage (*a remain ton*), which at the beginning of the simulation is equal to the entity's total tonnage. This attribute is calculated as $a\ block\ ton \times a\ fraction$;

Step 5 Calculate total input tonnage to the system.

Step 6 Hold the entity in a queue until the proper period is reached for extracting the corresponding mining-cut. If the current period of simulation (v period) is equal to the period that the mining-cut should be extracted (a period), go to Step 7

Step 7 Hold the entity in a queue until all precedent mining-cuts are completely depleted and the corresponding mining-cut is ready to be extracted. Meanwhile, search in the queue for any available mining-cuts for which all precedent mining-cuts are totally extracted, remove the corresponding entity from the queue, and send it through the system.

Step 8 If the entity is ore, calculate the total input ore tonnage (v1d input ore).If it is waste (v1d input waste) calculate the total input waste tonnage entering the system.

Step 9 Wait in a queue for a shovel to become available. As soon as a shovel is available, seize it.

Step 10 Wait in a queue for a truck to become available. As soon as a truck is available, seize it. The truck's current load-pass number (a load number) and load tonnage (a truck ton) are set to 0.

Step 11 Assign attributes of the truck. These attributes include the starting time of truck's cycle (a start time truck cycle), which is equal to the current time of simulation; and the starting shift of truck's cycle (a start shift truck cycle), which is equal to the current shift in simulation.

Step 12 The truck and the shovel travel to the mining-cut's location. The time that it takes for a couple of them to reach to the entity's location is the maximum value between the following two values:

- The time that it takes the shovel to travel to the entity's location, which is calculated as:

$$Time_1 = \frac{distance\ between\ shovel\ and\ mining\text{ - }cut}{shovel's\ movement\ velocity}$$

$$= \frac{\sqrt{\left(shovel_x \text{ - } cut_x\right)^2 + \left(shovel_y \text{ - } cut_y\right)^2 + \left(shovel_z \text{ - } cut_z\right)^2}}{shovel's\ movement\ velocity}$$

Where $shovel_x$, $shovel_y$, and $shovel_z$ are the coordinates of the shovel's location; and cut_x, cut_y, and cut_z are the coordinates of the mining-cut's location.

- The time that it takes the truck to travel to the entity's location, which is calculated as:

$$Time_2 = \frac{distance\ between\ pit\text{ - }exit\ and\ mining\text{ - }cut}{unloaded\ truck's\ movement\ velocity\ at\ the\ corresponding\ shift}$$

Step 13 When the truck and shovel arrive at the entity's location, assign new coordinates to the shovel (*v2d shovel coordinate*). The new coordinates are equal to the mining-cut's coordinates, because the shovel has arrived at the mining-cut and will be working there.

Step 14 Extract a portion of the mining-cut and load one load-pass onto the truck.

Step 15 Alter the attributes regarding the truck and load-passes. These alterations include:

- Increasing the truck's current load-pass number (*a load number*) by one unit;
- Assigning the current load-pass's tonnage (*a extraction ton*), which is equal to the minimum value between the shovel's bucket capacity and the mining-cut's remaining tonnage;
- Decrease the mining-cut's remaining tonnage (*a remain ton*) by the current load-pass's tonnage;
- Increase the truck's total load tonnage (*a truck ton*) by the current load-pass's tonnage.

Step 16 If the truck's load is ore, calculate the total extracted ore tonnage (*v extracted ore*). If it is waste, calculate the total extracted waste tonnage (*v extracted waste*).

Step 17 If the mining-cut is completely depleted and no more material is left, go to Step 18; otherwise go to Step 20.

Step 18 Mark the mining-cut as depleted by altering the variable that represents the situation of each mining-cut (*v1d precedence*).

Step 19 Release the shovel and go to Step 22.

Step 20 If the truck is not yet fully loaded, go to Step 14; otherwise go to Step 21.

Step 21 Duplicate the entity. The original entity goes to Step 10, and a new entity representing the truck goes to Step 22.

Step 22 The truck travels to its destination according to the type of entity it is hauling. The time that it takes for the truck to arrive at its destination is calculated as:

$$Time_3 = \frac{distance\ between\ pit\text{ - }exit\ and\ destination\ facility}{loaded\ truck's\ movement\ velocity\ at\ the\ corresponding\ shift}$$

Step 23 Decide about the truck's destination. If the destination is waste dump 1, go to Step 24; if it is waste dump 2, go to Step 28; if it is stockpile 1, go to Step 33; if it is stockpile 2, go to Step 37; if it is processing plant 1, go to Step 42; and if it is processing plant 2, go to Step 46.

Step 24 The truck waits in the queue at waste dump 1. As soon as a spot becomes available at waste dump 1, the truck seizes waste dump 1.

Step 25 The truck unloads the material at waste dump 1. It takes some time for the truck to dump its load.

Step 26 Calculate variables representing characteristics of waste dump 1 at each period. These variables include the following:

- Average grade of phosphor, sulfur, and magnetic iron delivered to waste dump 1 at each period (*v1d wd1 p*, *v1d wd1 s*, and *v1d wd1 mwt*);
- Total tonnage of material delivered to waste dump 1at each period (*v1d wd1 ton*).

Step 27 Release waste dump 1 and go to Step 32.

Step 28 The truck waits in the queue at waste dump 2. As soon as a spot becomes available at waste dump 2, the truck seizes waste dump 2.

Step 29 The truck unloads the material to waste dump 2. It takes some time for the truck to dump its load.

Step 30 Calculate variables representing characteristics of waste dump 2 at each period. These variables include the following:

- Average grade of phosphor, sulfur, and magnetic iron delivered to waste dump 2 at each period (*v1d wd2 p*, *v1d wd2 s*, and *v1d wd2 mwt*);
- Total tonnage of material delivered to waste dump 2at each period (*v1d wd2 ton*).

Step 31 Release waste dump 2 and go to Step 32.

Step 32 Calculate variables representing characteristics of material delivered to both waste dumps, and go to Step 51. These variables include the following:

- Average grade of phosphor, sulfur, and magnetic iron, and total tonnage of material delivered to both waste dumps at each period (*v1d waste p*, *v1d waste s*, *v1d waste mwt*, and *v1d waste ton*);
- Average grade of phosphor, sulfur, and magnetic iron, and total tonnage of material delivered to both waste dumps at each shift (*v2d waste p shift*, *v2d waste s shift*, *v2d waste mwt shift*, and *v2d waste ton shift*);

Step 33 The truck waits in the queue at stockpile 1. As soon as a spot becomes available at stockpile 1, the truck seizes stockpile 1.

Step 34 The truck unloads the material to stockpile 1. It takes some time for the truck to dump its load.

Step 35 Calculate variables representing characteristics of stockpile 1 at each period. These variables include the following:

- Average grade of phosphor, sulfur, and magnetic iron delivered to stockpile 1 at each period (*v1d sp1 p*, *v1d sp1 s*, and *v1d sp1 mwt*);
- Total tonnage of material delivered to stockpile 1at each period (*v1d sp1 ton*).

Step 36 Release stockpile 1 and go to Step 41.

Step 37 The truck waits in the queue at stockpile 2. As soon as a spot becomes available at stockpile 2, the truck seizes stockpile 2.

Step 38 The truck unloads the material at stockpile 2. It takes some time for the truck to dump its load.

Step 39 Calculate variables representing characteristics of stockpile 2 at each period. These variables include the following:

- Average grade of phosphor, sulfur, and magnetic iron delivered to stockpile 2 at each period (*v1d sp2 p*, *v1d sp2 s*, and *v1d sp2 mwt*);
- Total tonnage of material delivered to stockpile 2at each period (*v1d sp2 ton*).

Step 40 Release stockpile 2 and go to Step 41.

Step 41 Calculate variables representing characteristics of material delivered to both stockpiles, and go to Step 51. These variables include the following:

- Average grade of phosphor, sulfur, and magnetic iron, and total tonnage of material delivered to both stockpiles at each period (*v1d stock p*, *v1d stock s*, *v1d stock mwt*, and *v1d stock ton*);
- Average grade of phosphor, sulfur, and magnetic iron, and total tonnage of material delivered to both stockpiles at each shift (*v2d stock p shift*, *v2d stock s shift*, *v2d stock mwt shift*, and *v2d stock ton shift*);

Step 42 The truck waits in the queue at processing plant 1. As soon as a spot becomes available at processing plant 1, the truck seizes processing plant 1.

Step 43 The truck unloads the material at processing plant 1. It takes some time for the truck to dump its load.

Step 44 Calculate variables representing characteristics of processing plant 1 at each period. These variables include the following:

- Average grade of phosphor, sulfur, and magnetic iron delivered to processing plant 1 at each period (*v1d pr1 p*, *v1d pr1 s*, and *v1d pr1 mwt*);
- Total tonnage of material delivered to processing plant 1at each period (*v1d pr1 ton*).

Step 45 Release processing plant 1 and go to Step 50.

Step 46 The truck waits in the queue at processing plant 2. As soon as a spot becomes available at processing plant 2, the truck seizes processing plant 2.

Step 47 The truck unloads the material to processing plant 2. It takes some time for the truck to dump its load.

Step 48 Calculate variables representing characteristics of processing plant 2 at each period. These variables include the following:

- Average grade of phosphor, sulfur, and magnetic iron delivered to processing plant 2 at each period (*v1d pr2 p*, *v1d pr2 s*, and *v1d pr2 mwt*);
- Total tonnage of material delivered to processing plant 2at each period (*v1d pr2 ton*).

Step 49 Release processing plant 2 and go to Step 50.

Step 50 Calculate variables representing characteristics of material delivered to both processing plants, and go to Step 51. These variables include the following:

- Average grade of phosphor, sulfur, and magnetic iron, and total tonnage of material delivered to both processing plants at each period (*v1d mill p*, *v1d mill s*, *v1d mill mwt*, and *v1d mill ton*);
- Average grade of phosphor, sulfur, and magnetic iron, and total tonnage of material delivered to both processing plants at each shift (*v2d mill p shift*, *v2d mill s shift*, *v2d mill mwt shift*, and *v2d mill ton shift*);

Step 51 Truck travels from the destination facility back to the pit-exit point. The time that it takes the truck to arrive to the pit-exit point is calculated as:

$$Time_4 = \frac{distance\ between\ pit\text{ - }exit\ and\ destination\ facility}{unloaded\ truck's\ movement\ velocity\ at\ the\ corresponding\ shift}$$

Step 52 Calculate the truck’s cycle time and count the number of truck cycles (*v2d truck cycle time* and *v2d truck cycle count*). Do the same calculations based on the destination to which the truck has travelled (*v2d truck cycle time des* and *v2d truck cycle count des*).

Step 53 Release the truck.

Step 54 Dispose the corresponding entity.

Figure 3 and Figure 4 show the flowchart of the main model with the number of each step tagged on the flowchart. This flowchart summarizes the procedures of Step 1 to Step 54.

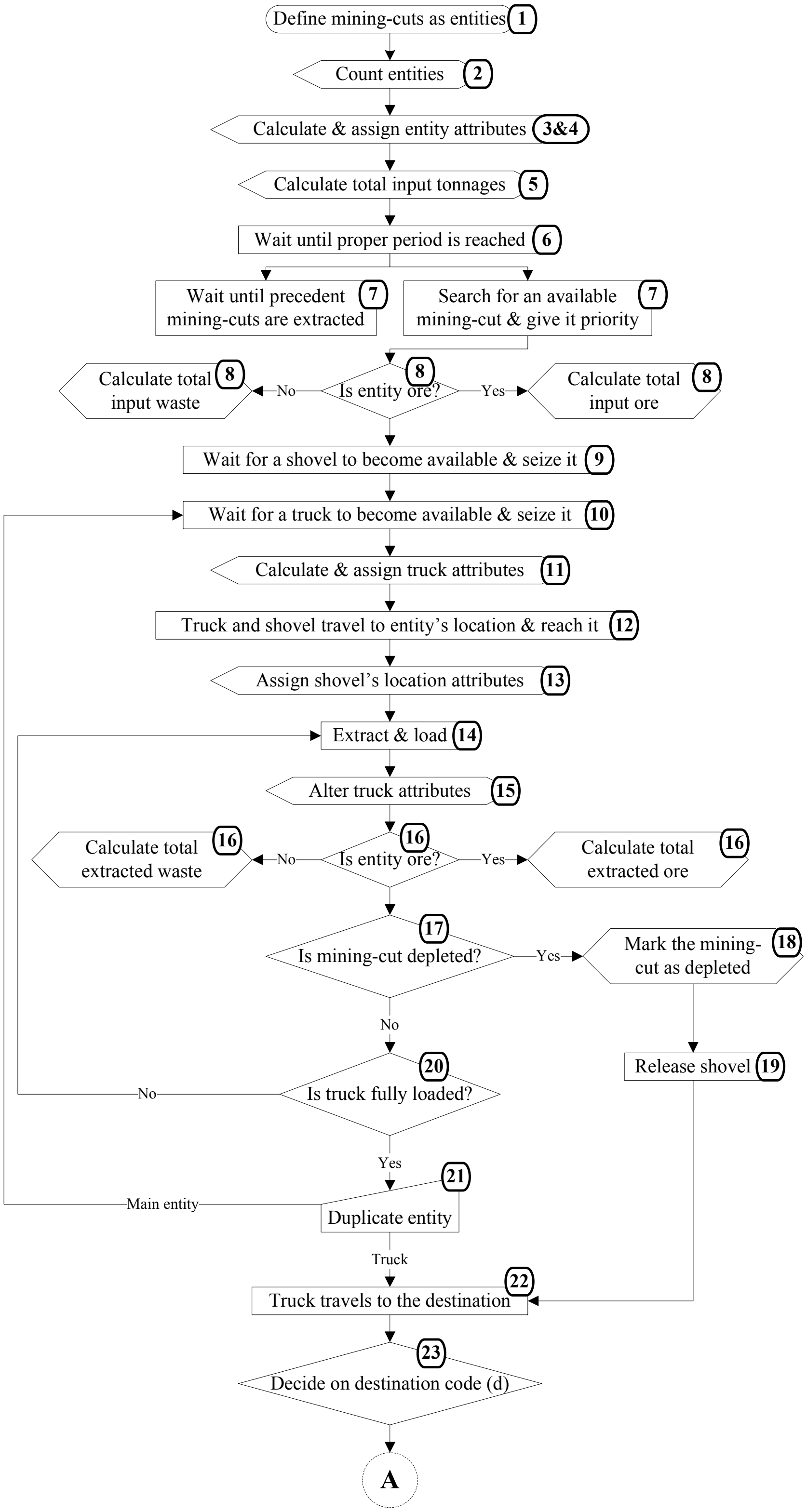

Figure 3. Flow chart of the main simulation model with tagged step numbers (part 1)

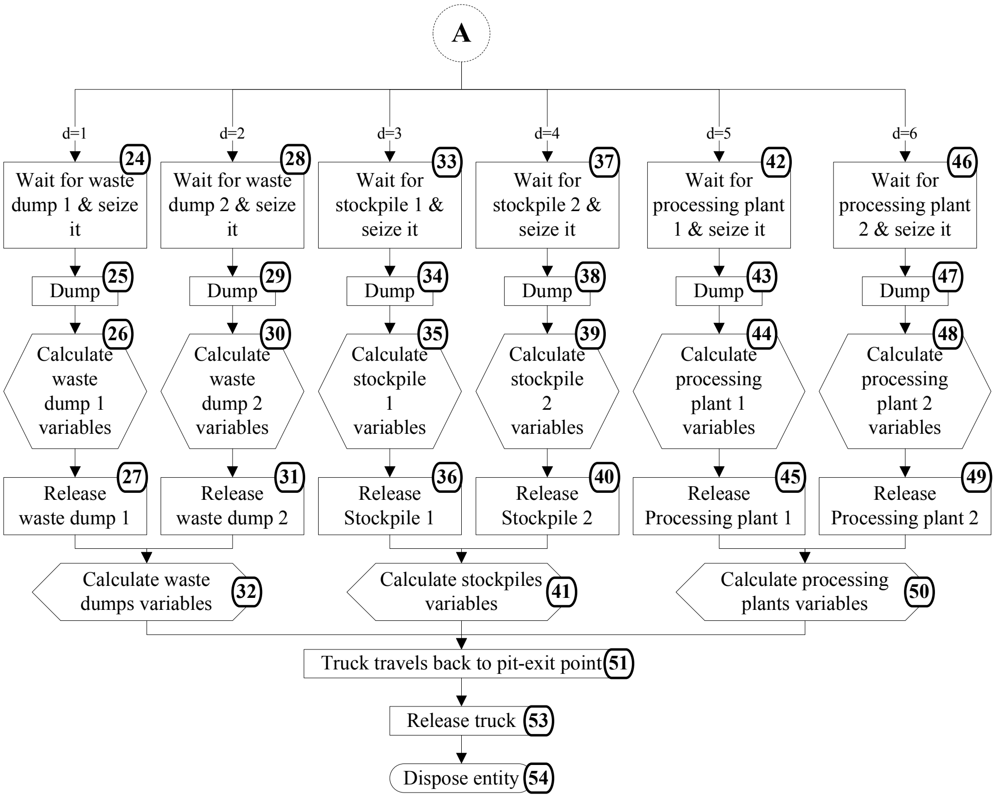

Figure 4. Flow chart of the main simulation model with tagged step numbers (part 2)

3.2.3.2 Reclamation Sub-model

Step 55 Define entities representing material that will be reclaimed from stockpile 2 at each period (*ent reclamation*). The maximum number of reclamation entities is equal to the maximum number of periods.

Step 56 Increase the global variable counting reclamation entities of stockpile 2 (*v reclamation material number sp2*) by one unit.

Step 57 Make the reclamation entity's number (*a block number*) equal to *v reclamation material number sp2*. The main entity's number is its identification number (ID) in the simulation model.

Step 58 Assign reclamation entity's attributes which are determined directly by the optimal short-term schedule. These attributes include:

- The period number in which the reclamation is performed (*a period*);
- The grade of magnetic iron (*a mwt*);

- The entity's total tonnage (a entity ton)
- The entity's remaining tonnage (*a remain ton*) which at the beginning of the simulation is equal to the entity's total tonnage.

Step 59 Hold the entity in a queue until the proper period is reached for the reclamation process. If the current period of simulation (*v period*) is equal to the period of reclamation (*a period*), go to Step 60.

Step 60 Wait in a queue for the loader and a reclamation truck to become available. As soon as a loader and a reclamation truck are available, seize them.

Step 61 The loader fully loads the truck.

Step 62 Alter the attributes regarding the truck and load-passes. These alterations include:

- Assigning the current load-pass's tonnage (*a extraction ton*), which is equal to the minimum value between the loader's bucket capacity and the remaining tonnage in the stockpile;
- Decreasing the remaining tonnage in the stockpile (*a remain ton*) by the current load-pass's tonnage;
- Increasing the truck's total load tonnage (*a truck ton*) by the current load-pass's tonnage.

Step 63 Release the loader.

Step 64 Duplicate the original reclamation entity. The original reclamation entity goes to Step 65. The duplicate, which represents the truck, goes to Step 66.

Step 65 If there is still material in the stockpile for reclamation, go to Step 60; otherwise, dispose of the entity.

Step 66 The truck travels from the stockpile to the corresponding processing plant. The time that it takes the truck to arrive to the processing plant is calculated as:

$$Time_5 = \frac{distance\ between\ stockpile\ 2\ and\ processing\ plant\ 2}{loaded\ truck's\ movement\ velocity\ at\ the\ corresponding\ shift}$$

Step 67 The truck waits in the queue at processing plant2. As soon as a spot becomes available at processing plant2, the truck seizes it.

Step 68 The truck unloads the material at processing plant2. It takes some time for the truck to dump its load.

Step 69 Calculate variables representing characteristics of reclaimed material at each period. These variables include the following:

- Average grade of magnetic iron reclaimed from stockpile 2at each period (*v1d sp2topr2 mwt*);
- Total tonnage of material reclaimed from stockpile 2at each period (*v1d sp2topr2 ton*).

Step 70 Release processing plant 2.

Step 71 The truck travels from processing plant 2 back to stockpile 2. The time that it takes the truck to arrive to the pit-exit point is calculated as:

$$Time_6 = \frac{distance\ between\ stockpile\ 2\ and\ processing\ plant\ 2}{unloaded\ truck's\ movement\ velocity\ at\ the\ corresponding\ shift}$$

Step 72 Release the truck.

Step 73 Dispose of the corresponding entity.

It is also possible to reclaim material from stockpile 1 and deliver it to processing plant 1. For such operations, a similar procedure (Step 55 to Step 73) is implemented. The only difference is that the model considers stockpile1 instead of stockpile 2, and processing plant 1 instead of processing plant 2. In other words, this sub-model uses all characteristics, variables and attributes related to stockpile 1 and processing plant 1.

The flowchart of the reclamation sub-model with the number of each step tagged on the flowchart is represented in Figure 5. This flowchart summarizes the procedure of Step 55 to Step 73.

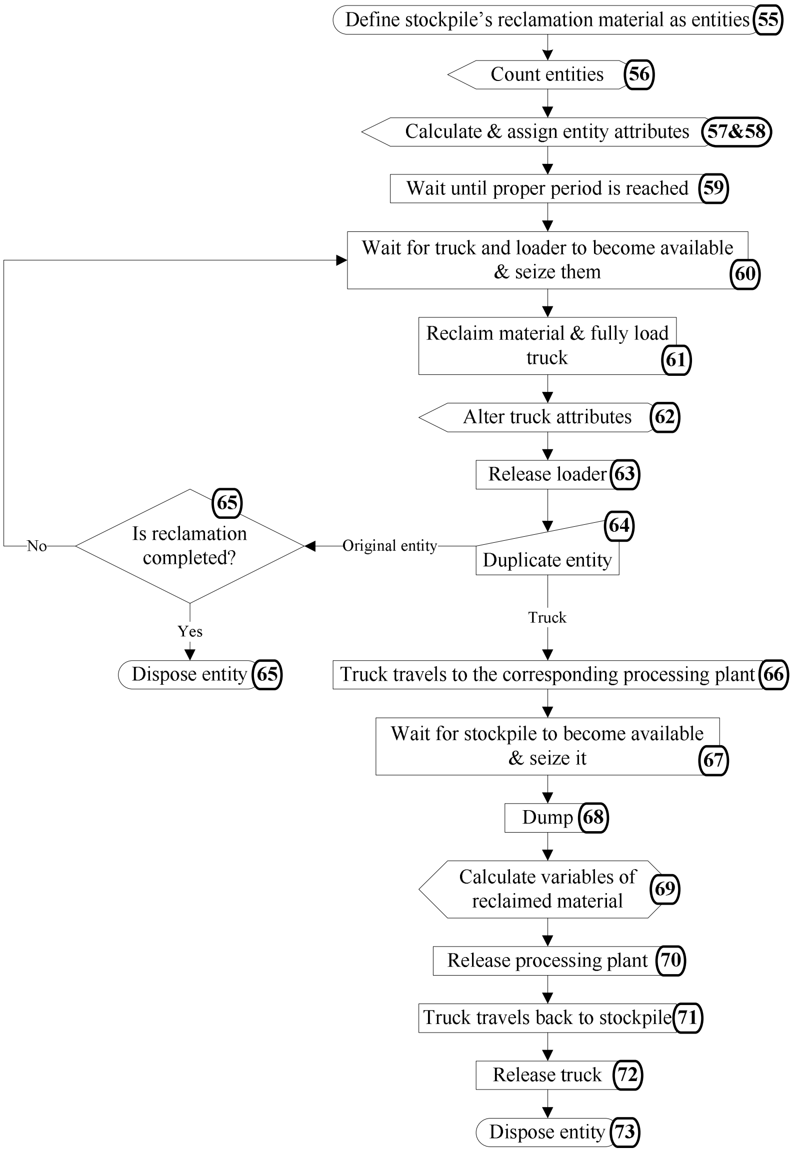

Figure 5. Flowchart of the reclamation sub-model with tagged step numbers

3.2.3.3 Modifications

As mentioned before, among system KPIs, truck waiting time is one of the most important ones that this study tries to improve. To improve truck waiting time, a new scenario with some new assumptions is introduced. It is assumed that if a truck that is hauling ore and going to a processing plant faces the crusher failure, the truck would not wait for the crusher to become available. The truck would travel to the corresponding stockpile and deliver material to the stockpile.

To deal with the new assumptions, some alterations are made to the model. Step 58 is modified in the following way. In period 1, the reclamation entity's tonnage and grades are assigned based on the optimal short-term schedule. In the subsequent periods, the tonnage and grade of reclamation entity are calculated differently. At period *n* (*n*>*1*), the tonnage of the reclamation entity is calculated as the sum of tonnage from the planned flow of material at period *n* and tonnage from the unplanned flow of material at period *n-1*. Also, the average grade of reclaimed material is the weighted average grades from the aforementioned flows of material.

In addition, Step 21.a, Step 21.b, Step 21.c, and Step 21.d are added between Step 21 and Step 22 as follows. The summary of these steps is pictured in Figure 6.

Step 21.a. If the truck is going to processing plant 1 and processing plant 1 is failed, go to Step 21.b; otherwise go to Step 21.c.

Step 21.b. Change the truck's destination (*a destination*) to processing plant 1; Mark the truck as hauling unplanned flow of material by changing entity type (*ent unplanned flow 1*); and go to Step 22.

Step 21.c. If the truck is going to processing plant 2 and processing plant 2 is failed, go to Step 21.d; otherwise go to Step 22.

Step 21.d. Change the truck's destination (*a destination*) to processing plant 2; Mark the truck as hauling unplanned flow of material by changing entity type (*ent unplanned flow 2*); and go to Step 22.

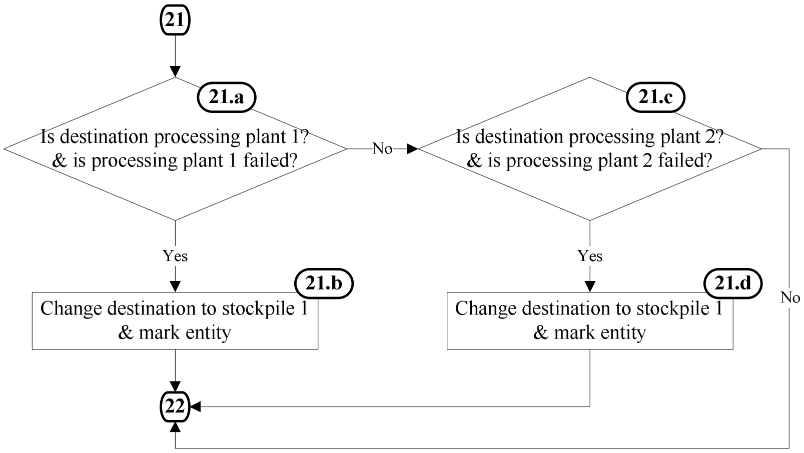

Figure 6. Flowchart of the modifications (part 1)

Moreover, Step 23.a and Step 23.b are added between Step 23 and Step 33. Step 23.c and Step 23.d are added between Step 23 and Step 37. Figure 7 illustrates these steps.

Step 23.a. If the entity type is *ent unplanned flow 1* go to Step 23.b; otherwise go to Step 33.

Step 23.b. Calculate variables representing characteristics of unplanned material flow from going to stockpile 1 Step 33. These variables include:

- Average grade of phosphor, sulfur, and magnetic iron delivered to stockpile 1 at each period as a result of unplanned flow (*v1d pr1tosp1 p*, *v1d pr1tosp1 s*, and *v1d pr1tosp1 mwt*);
- Total tonnage of material delivered to stockpile 1at each period as a result of unplanned flow (*v1d pr1tosp1 ton*).

Step 23.c. If the entity type is *ent unplanned flow 2* go toStep 23.d; otherwise go to Step 37.

Step 23.d. Calculate variables representing characteristics of unplanned material flow from going to stockpile 2; and go to Step 37. These variables include:

- Average grade of phosphor, sulfur, and magnetic iron delivered to stockpile 2 at each period as a result of unplanned flow (*v1d pr2tosp2 p*, *v1d pr2tosp2 s*, and *v1d pr2tosp2 mwt*);
- Total tonnage of material delivered to stockpile 1at each period as a result of unplanned flow (*v1d pr2tosp2 ton*).

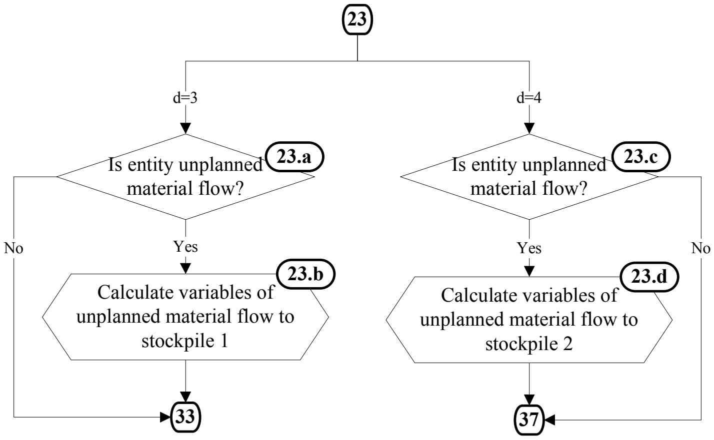

Figure 7. Flowchart of the modifications (part 2)

3.3 Summary and Remarks

In summary, this chapter has presented the MILP model to allocate trucks and shovels to mining-faces. The procedure used to solve the MILP model and integrate it with the simulation model is suggested for future research. Also, the theoretical framework and procedure used to simulate truck-and-shovel operations and integrate them with the short-term production plan has been discussed in this chapter. In the simulation model, characteristics of mining-cuts, the extraction precedence between them, and uncertainties associated with truck-and-shovel operations are considered. The theoretical framework has explained the following procedures:

- Determining the required numbers of trucks and shovels in situations where resources do not fail, as well as situations where resource failures happen;

- Developing a maintenance schedule because of possible variations in truck and shovel utilizations in different periods;
- Assessing KPIs of the system, employing the chosen numbers of trucks and shovels;
- Improving the system by reducing truck waiting time at processing plants.

The steps implemented in simulation model are summarized as:

- An entity enters the system, and waits until the proper period is reached for the extraction and all precedent mining-cuts are extracted.
- The entity seizes a truck and a shovel, and the truck and shovel travel to the entity location. The shovel extracts a portion of the mining-cut and loads it until the truck is fully loaded or the mining-cut is depleted.
- The truck travels to the pit-exit point and from there to the predetermined destination. If the truck's destination is a processing plant and the crusher fails, the truck travels to the corresponding stockpile.
- The truck seizes the destination, dumps its load, and travels back to the pit-exit point.
- For the reclamation process, similar activities are done for each stockpile that feeds the corresponding processing plant.

CHAPTER 4

CASE STUDY AND DISCUSSION OF RESULTS

The simulation model developed in Chapter 3 is implemented on a real mine using Arena (Rockwell Automation, 2010) simulation software. This chapter applies the proposed simulation model, which is linked to the optimal short-term production schedule of an open-pit mine, Gol-E-Gohar, in the south of Iran. In addition, this chapter is concerned with verifying the simulation model.

4.1 Case Study

The open-pit mine under study has a large pit with a unique pit-exit point. Extracted material is hauled to the pit-exit point through two ramps, including 34 ramp segments, before being sent to final destinations. The six destinations in the mine include two waste dumps, two stockpiles, and two processing plants. It is assumed that stockpile 1 feeds only crusher 1 and stockpile 2 feeds only crusher 2.

Figure 8 shows the schematic view of the mine and the distances between the pit-exit point and different destinations, as well as the distances between the processing plants and the corresponding stockpiles.

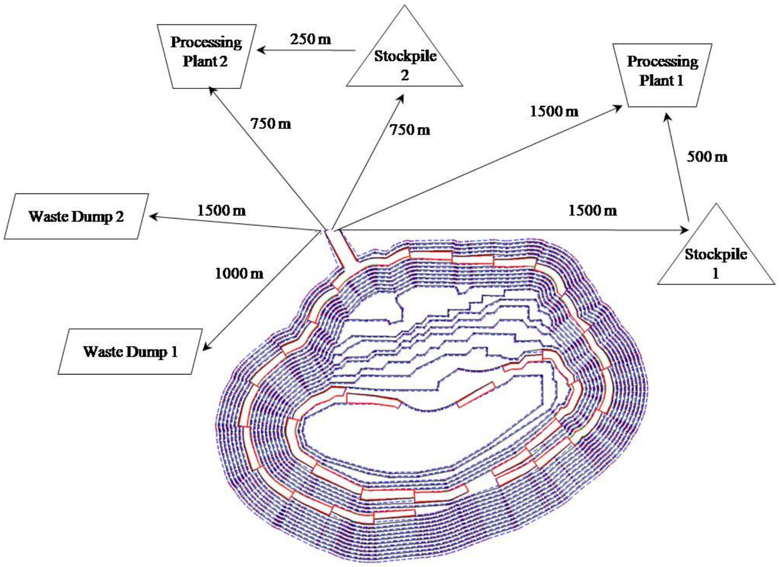

Figure 8. Schematic view of the mine

The total mining capacity of the mine is 2.2 million tonnes per month. The upper and lower bounds on the monthly processing capacity of each of the processing plants are 0.32 million tonnes and 0.4 million tonnes, respectively. There is no limit on the capacities of stockpiles and waste dumps. The main element of interest in the deposit is iron, for which magnetic weight recovery (MWT) is measured. The contaminants are phosphor and sulfur, considered as secondary elements to be controlled. The upper and lower bounds on the element grades at processing plants and stockpiles are represented in Table 1. There are no grade bounds for material delivered to waste dumps.

Table 1. Upper and lower limits of grades at destinations

Destination	Element	Lower Grade (%)	Upper Grade (%)	Output Grade (%)
Processing Plant 1	MWT	73	78	-
	Phosphor	0	0.3	-
	Sulfur	0	2	-
Processing Plant 2	MWT	78	82	-
	Phosphor	0	0.3	-
	Sulfur	0	2	-
Stockpile 1	MWT	71	74	72.5
	Phosphor	0	0.3	1.5
	Sulfur	0	3	0.15
Stockpile 2	MWT	75	77	76
	Phosphor	0	0.35	1
	Sulfur	0	2	0.17

The optimal short-term production plan for this mine is developed by Eivazy and Askari-Nasab (2012) for a time horizon of one year, with monthly resolutions. This schedule is shown in Figure 9. In the short-term schedule generated by these researchers, blocks are aggregated into practical scheduling units which are referred to as mining-cuts. The total number of mining-cuts that should be extracted during this year is 330. Total rock tonnage and ore tonnage of these mining-cuts are 25 and 8 million tonnes, respectively. Each mining-cut can have fiveblocks on average and a maximum of 10 blocks. Table 2shows the characteristics of the mining-cuts presented in the short-term schedule.

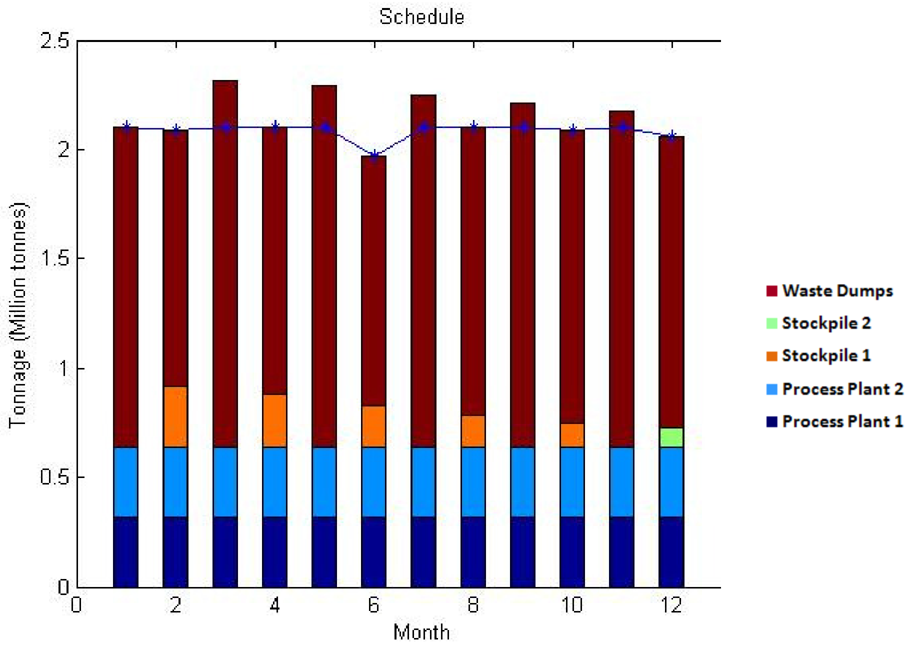

Figure 9. Optimal short-term schedule developed by Eivazy and Askari-Nasab (2012)

Table 2. Characteristics of mining-cuts

		Minimum	Maximum
Coordinate (m)	X	97,503.13	98,968.75
	Y	600,187.5	601,100
	Z	1,560	1,725
Material Content (thousand tonnes)	Total	1.63	250.16
	Ore	0	237.65
	Waste	0.75	138.75
Grade (%)	MWT	0	0.82
	Phosphor	0	0.02
	Sulfur	0	0.002
Distance to Pit-exit Point (m)		774.92	2,375.61
Number of Precedent Mining-cuts		0	11

The mine employs CAT 785D mining trucks and CAT 7295 HD electric rope shovels. The truck’s nominal payload capacity is about 120 tonnes and the shovel’s nominal dipper payload capacity is about 40 tonnes. So, a truck is fully loaded by three load-passes. The equipment works 24 hours a day: one day shift and one night shift.

The simulation model deals with the uncertainties associated with the operations of trucks and shovels. These uncertainties include the tonnage that a shovel can extract at each load-pass; the time that it takes to complete one load-pass; the time that it takes to complete the dumping action; the moving velocity of a shovel during day and night shifts; the velocity of a loaded truck and an empty truck during day and night shifts; and failures of trucks, shovels and crushers.

Each stochastic variable is represented with a probability density function. Regarding failures of resources, the commonly used probability density functions to define the MTBF and the MTTR are Weibull and Gamma density functions, respectively. For the rest of the random variables, data analysis is performed on historical dispatching data gathered from a Jigsaw dispatching database. To fit the best probability density function, Arena Input Analyzer is used. Table 3 presents the random variables and their representative probability density functions.

Table 3. Stochastic variables and their representative probability density functions

Stochastic Variable	Probability Density Function
Loaded Truck Velocity During Day Shift (km/h)	Normal (18, 3)
Loaded Truck Velocity During Night Shift (km/h)	Triangular (15, 15, 18)
Empty Truck Velocity During Day Shift (km/h)	Normal (36, 3)
Empty Truck Velocity During Night Shift (km/h)	Triangular (30, 30, 33)
Shovel Velocity During Day Shift (km/h)	Normal (6, 0.6)
Shovel Velocity During Night Shift (km/h)	Triangular (5.1, 5.1, 5.7)
Load Time (s)	Triangular (12, 15, 18)
Dump Time (s)	Triangular (10.2, 12, 15)
Load-pass Tonnage (tonnes)	Triangular (30, 35, 40)
MTBF for Truck Minor Failure (h)	Wibull (27, 200)
MTTR for Truck Minor Failure (h)	Gamma (1.4, 1.5)
MTBF for Truck Major Failure (h)	Weibull (65, 200)
MTTR for Truck Major Failure (h)	Gamma (0.25, 24)
MTBFfor Shovel Failure (h)	Weibull (32, 216)
MTTRfor Shovel Failure (h)	Gamma (1.4, 1.5)
MTBF for Crusher Failure (h)	Weibull (90, 200)
MTBR for Crusher Failure (h)	Gamma (0.25, 24)

It is assumed that only one truck can dump at each of the processing plants or each of the stockpiles at the same time. There is room for only three trucks at each of the waste dumps.

The proposed simulation model is developed using Arena (Rockwell Automation, 2010) simulation software. The model reads all input data from an Excel.csv format file for easier input data entry and modifications. The model also exports all variable estimates, averages, and counts to an Excel.csv format file to more easily analyze output variables.

4.2 Determining Numbers of Trucks and Shovels

When designing and studying the truck-and-shovel system, the first sub-problem is to determine the required numbers of trucks and shovels. To do so, different scenarios are generated using Arena Process Analyzer (Rockwell Automation, 2010). The procedure starts to build scenarios with small numbers of trucks and shovels, and increases them in the consecutive scenarios.

First, a fixed number of shovels is considered, and the effect of increasing the number of trucks is studied. Then, the number of shovels is increased by one unit, and with the new number of shovels the effect of increasing the number of trucks is studied again. This procedure is repeated with different numbers of shovels until the production target is met. Once the production target is met, more scenarios can be studied, but it is not necessary.

In this sub-problem, the variable under control is the numbers of trucks and shovels, which differs depending on the scenario. The criteria used to evaluate each scenario are the production level, average shovel utilization, and average truck utilization. Scenarios in which the production target is met are considered feasible scenarios. The best scenario is a feasible scenario with the highest truck and shovel utilizations.

In the initial scenario analysis, it is assumed that none of the trucks, shovels or crushers fails at any time. As shown in Figure 10 and Table 4, there is more than just one feasible scenario, such as scenarios 10, 11, 14, and 15. In these scenarios, the production target, which is 25 million tonnes, is met. As explained before, the best of these scenarios is the one with the highest utilizations. Therefore, scenario 10, with almost 81% average shovel utilization and 84% average truck utilization, is the best one. According to this scenario, at least two shovels and eight trucks are needed to meet the production target and obtain the highest truck-and-shovel utilizations.

In the second scenario analysis, all failures of trucks, shovels, and crushers are considered as well as the inactive time between shift changes. As shown in Figure 11 and Table 5, scenario generation starts with two shovels and four trucks, and increases to four shovels and 15 trucks. With a fixed number of shovels, for example two shovels, scenarios 1 to 12 are generated by increasing the number of trucks. As the number of trucks increases, more material is extracted (scenarios 1 to 9). After a point (about scenario 9), further increasing the number of trucks will not result in much higher production. On the contrary, it will reduce the utilizations.

When such behavior is observed, the number of shovels is increased by one unit and the aforementioned procedure is repeated. In scenario 18, with three shovels and 11 trucks, the production target is met. The average shovel utilization is about 89% and the average truck utilization is about 67% in this scenario. Accordingly, this scenario is chosen as the best scenario. Further increasing the number of shovels or trucks produces more feasible scenarios but decreases the utilizations.

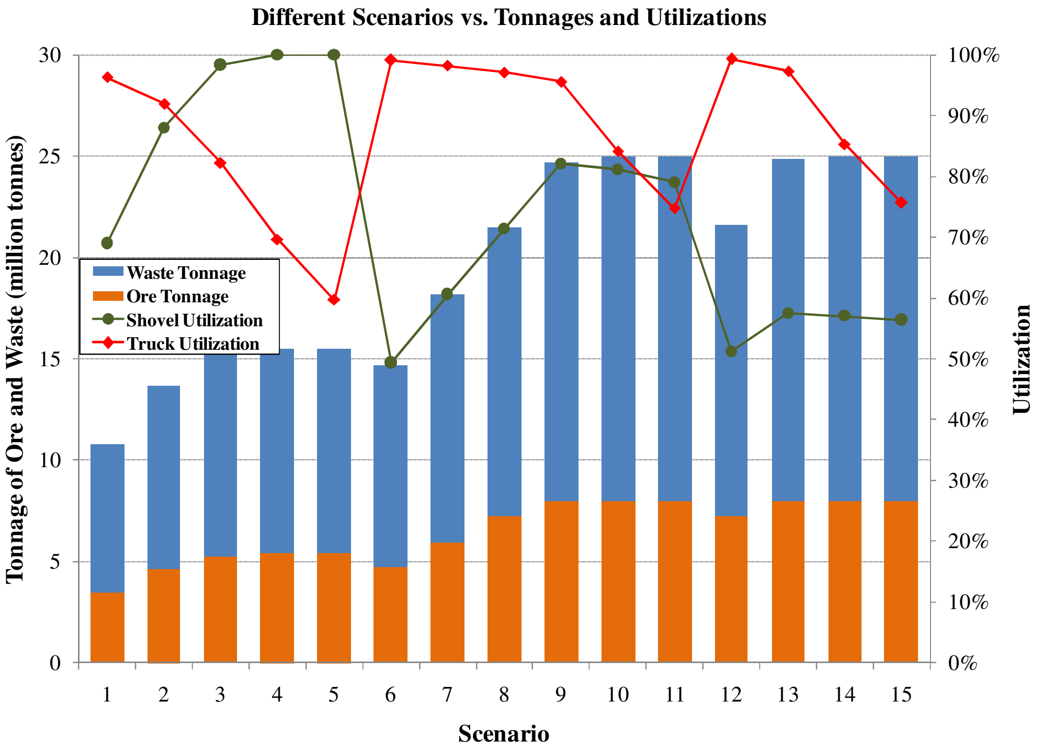

Figure 10. Delivered material tonnage and resource utilizations in initial scenario analysis

Table 4. Delivered material tonnage and resource utilizations in initial scenario analysis

Scenario	Number of Shovels	Number of Trucks	Delivered Ore Tonnage (million tonnes)	Delivered Waste Tonnage (million tonnes)	Average Shovel Utilization (%)	Average Truck Utilization (%)
1	1	3	3.46	7.31	68.97	96.27
2	1	4	4.63	9.00	87.92	91.96
3	1	5	5.23	10.07	98.31	82.27
4	1	6	5.42	10.08	99.97	69.61
5	1	7	5.42	10.08	100.00	59.68
6	2	4	4.75	9.92	49.34	99.08
7	2	5	5.95	12.20	60.57	98.20
8	2	6	7.23	14.24	71.30	97.09
9	2	7	7.99	16.71	81.22	95.54
10	2	8	7.99	17.01	81.08	84.15
11	2	9	7.99	17.01	80.53	74.74
12	3	6	7.26	14.32	51.12	99.29
13	3	7	7.99	16.87	57.43	97.28
14	3	8	7.99	17.01	57.00	85.25
15	3	9	7.99	17.01	56.40	75.62

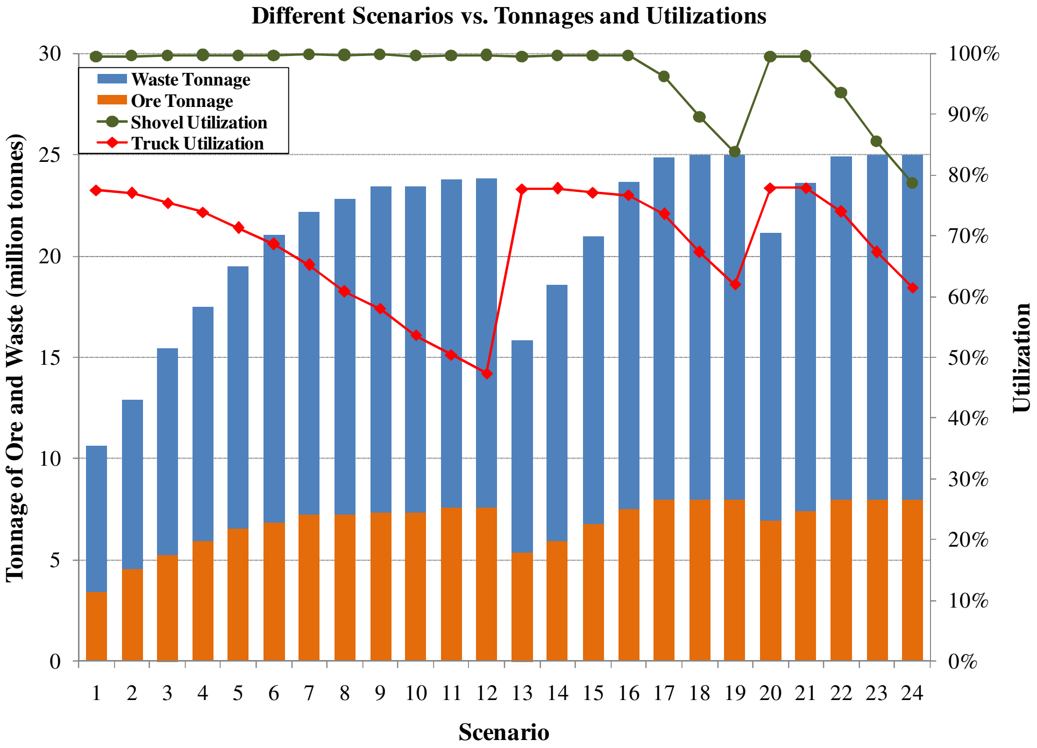

Figure 11. Delivered material tonnage and resource utilizations in second scenario analysis

The average truck and shovel utilizations during each month are monitored based on the pre-set numbers of 11 trucks and three shovels. As presented in Figure 12 and Table 6, the average truck and shovel utilizations vary during different months. The average utilizations in the odd months (1, 3, 5, 7, 9, and 11) are almost less than those in the even months (2, 4, 6, 8, 10, and 12). This is because during months 3, 5, 7, and 9, less material has been delivered directly from the mine to the processing plants. Instead, some material is reclaimed from stockpiles during these months (see Figure 17).

In order to make sure that the equipment on-site is used during odd months, the mine may have less equipment on hand during those months. That way, workers at the mine will have to use everything available. To study the feasibility of such an alternative, another scenario analysis is implemented with the focus on odd months. Employing less equipment during some periods is defined as introducing scheduled maintenance for the inactive equipment during those periods.

Table 5. Delivered material tonnage and resource utilizations in second scenario analysis

Scenario	Number of Shovels	Number of Trucks	Delivered Ore Tonnage (million tonnes)	Delivered Waste Tonnage (million tonnes)	Average Shovel Utilization (%)	Average Truck Utilization (%)
1	2	4	3.43	7.19	99.42	77.49
2	2	5	4.54	8.36	99.54	76.97
3	2	6	5.22	10.22	99.58	75.39
4	2	7	5.95	11.54	99.66	73.85
5	2	8	6.56	12.89	99.57	71.26
6	2	9	6.84	14.19	99.62	68.62
7	2	10	7.26	14.92	99.78	65.18
8	2	11	7.26	15.52	99.65	60.78
9	2	12	7.34	16.08	99.82	57.95
10	2	13	7.35	16.08	99.54	53.57
11	2	14	7.57	16.19	99.55	50.38
12	2	15	7.61	16.24	99.68	47.31
13	3	6	5.36	10.44	99.38	77.7
14	3	7	5.95	12.63	99.63	77.72
15	3	8	6.78	14.19	99.55	77.09
16	3	9	7.50	16.16	99.58	76.65
17	3	10	7.99	16.90	96.13	73.55
18	3	11	7.99	17.01	89.48	67.28
19	3	12	7.99	17.01	83.7	61.97
20	4	8	6.93	14.20	99.41	77.88
21	4	9	7.44	16.15	99.45	77.89
22	4	10	7.99	16.93	93.43	73.9
23	4	11	7.99	17.01	85.41	67.25
24	4	12	7.99	17.01	78.63	61.49

he purpose of the third scenario analysis is to study the possibility of employing less equipment in odd months to increase its use during these months. Based on the results from the previous scenario analysis, three shovels and 11 trucks were chosen for the truck-and-shovel system. So, in the third scenario analysis, scenarios with fewer than three shovels or fewer than 11 trucks are examined. In all scenarios, three shovels and 11 trucks are fixed for even months. The numbers of trucks and shovels for the odd months differs from one scenario to another. Generated scenarios and results are presented in Figure 6 and Table 7. Scenario 17, with three shovels and 10 trucks, is the best scenario that meets the 25 million tonne production target and generates the highest utilizations. This means that the mine employs three shovels and 11 trucks during the year, but in odd months it does not use one of the trucks because of scheduled maintenance.

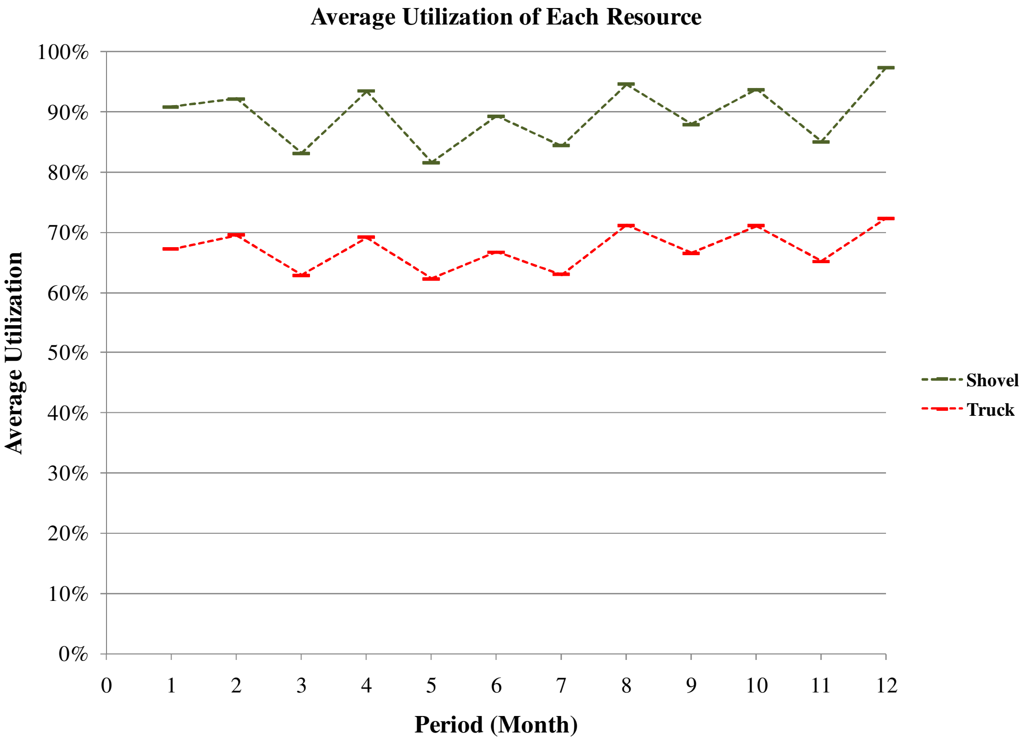

Figure 12. Average utilization of resources with three shovels and 11 trucks

Table 6. Average utilization of resources with three shovels and 11 trucks

Month	Average Shovel Utilization (%)	Average Truck Utilization (%)
1	90.83	67.21
2	92.25	69.58
3	83.13	62.93
4	93.51	69.20
5	81.59	62.26
6	89.30	66.74
7	84.41	62.97
8	94.60	71.21
9	87.93	66.55
10	93.73	71.13
11	85.06	65.22
12	97.40	72.38

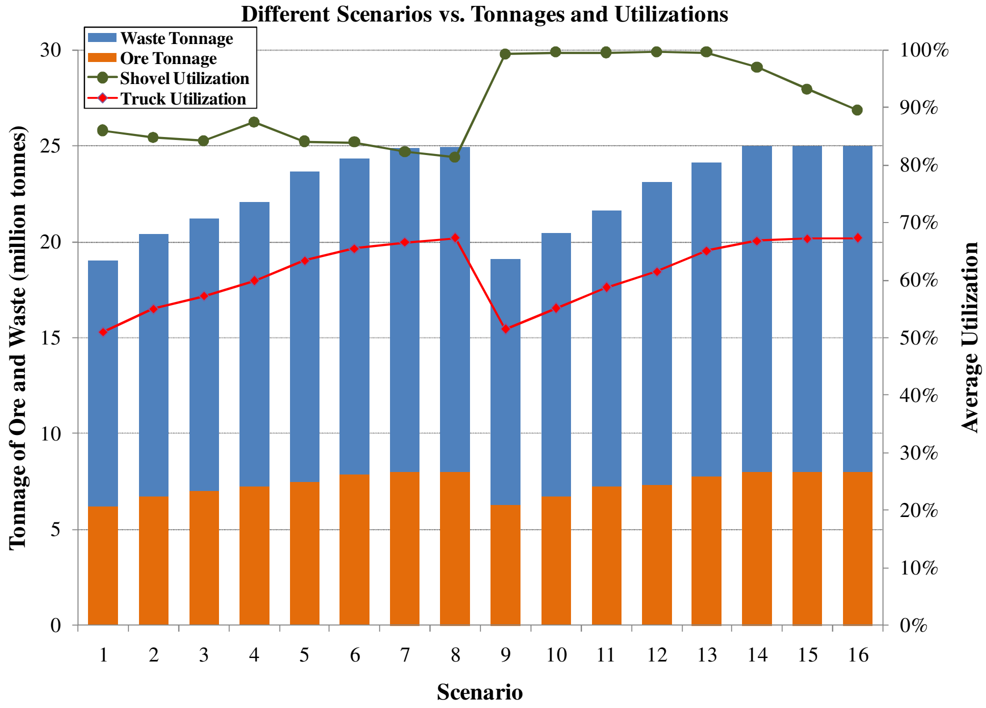

Figure 13.Delivered material tonnage and resource utilizations in third scenario analysis

Table 7. Delivered material tonnage and resource utilizations in third scenario analysis

Scenario	In odd months		Delivered Ore Tonnage (million tonnes)	Delivered Waste Tonnage (million tonnes)	Average Shovel Utilization (%)	Average Truck Utilization (%)
	Number of Shovels	Number of Trucks				
1	2	4	6.20	12.80	85.97	50.99
2	2	5	6.70	13.68	84.71	54.94
3	2	6	7.00	14.19	84.16	57.21
4	2	7	7.26	14.77	87.38	59.82
5	2	8	7.49	16.14	84.05	63.38
6	2	9	7.89	16.46	83.89	65.49
7	2	10	7.97	16.90	82.24	66.55
8	2	11	7.98	16.93	81.25	67.23
11	3	4	6.30	12.80	99.17	51.46
12	3	5	6.70	13.77	99.51	55.08
13	3	6	7.26	14.34	99.50	58.65
14	3	7	7.32	15.77	99.61	61.50
15	3	8	7.77	16.32	99.51	65.07
16	3	9	7.99	16.96	96.92	66.75
17	3	10	7.99	17.01	93.14	67.21
18	3	11	7.99	17.01	89.48	67.28

At this stage, the average monthly equipment utilizations are monitored again to see the effect of defining the maintenance schedule for one of the trucks. The resulting average truck and shovel utilizations are shown in Figure 14 and Table 8. Compared to the previous scenario, which uses fixed numbers of trucks and shovels throughout the year, the new scenario results in steadier equipment utilization. Defining a maintenance schedule is important because in addition to ensuring that equipment is used on a steadier basis, it causes less wear, and saves more money on personnel.

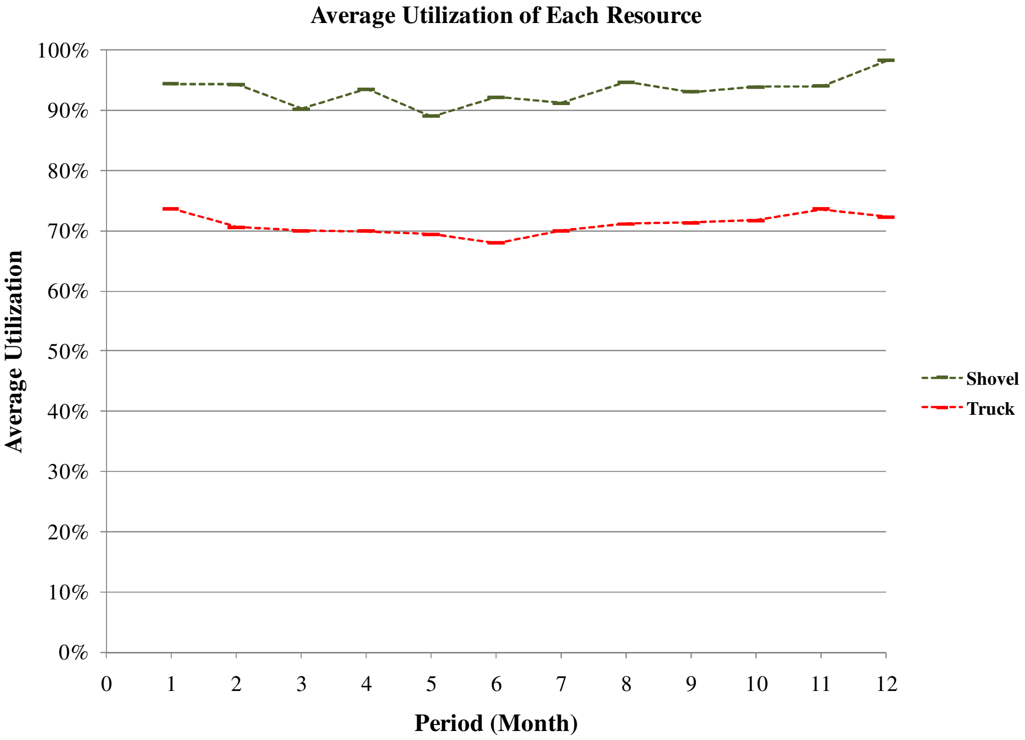

Figure 14. Average utilizations of resources considering maintenance schedule

Table 8. Average utilizations of resources considering maintenance schedule

Month	Numberof Shovels	Numberof Trucks	Average Shovel Utilization (%)	Average Truck Utilization (%)
1	3	10	94.46	73.70
2	3	11	94.31	70.59
3	3	10	90.28	70.06
4	3	11	93.61	69.96
5	3	10	89.08	69.48
6	3	11	92.24	68.03
7	3	10	91.21	69.99
8	3	11	94.71	71.17
9	3	10	93.12	71.40
10	3	11	93.97	71.74
11	3	10	94.08	73.62
12	3	11	98.30	72.31

4.3 Evaluating Key Performance Indicators

Using three shovels and 10 trucks in odd months, and three shovels and 11 trucks in even months, the simulation model is run for 50 replications. This number of replications gives acceptable KPI half-widths, which are explained in section 4.6. One of the most important KPIs is the average utilization of trucks and shovels. Because of stochastic variables taken into account in the model, each replication gives a different average utilization of equipment.

To show the results clearly, box plots are used in this study. Because of the small size of a box plot, it is easy to display and compare several box plots in a small space. Each box plot is a short graphical representation of a set of data resulting from a set of replications. Each set of data can also be shown by a histogram. Because box plots are small, it is easier to display and compare several box plots in a small space than to do the same with histograms.

The box plot summarizes the statistics of a set of data with five numbers. The top and the bottom of the box represent the upper quartile (75th percentile) and the lower quartile (25th percentile) respectively. The line in the middle of the box shows the median (50th percentile). Ends of the upper and lower whiskers indicate the maximum and minimum values respectively. The box plots of the average utilization of shovels and trucks and the corresponding statistics are shown in Figure 15 and Figure 16, and Table 9 and Table 10 respectively.

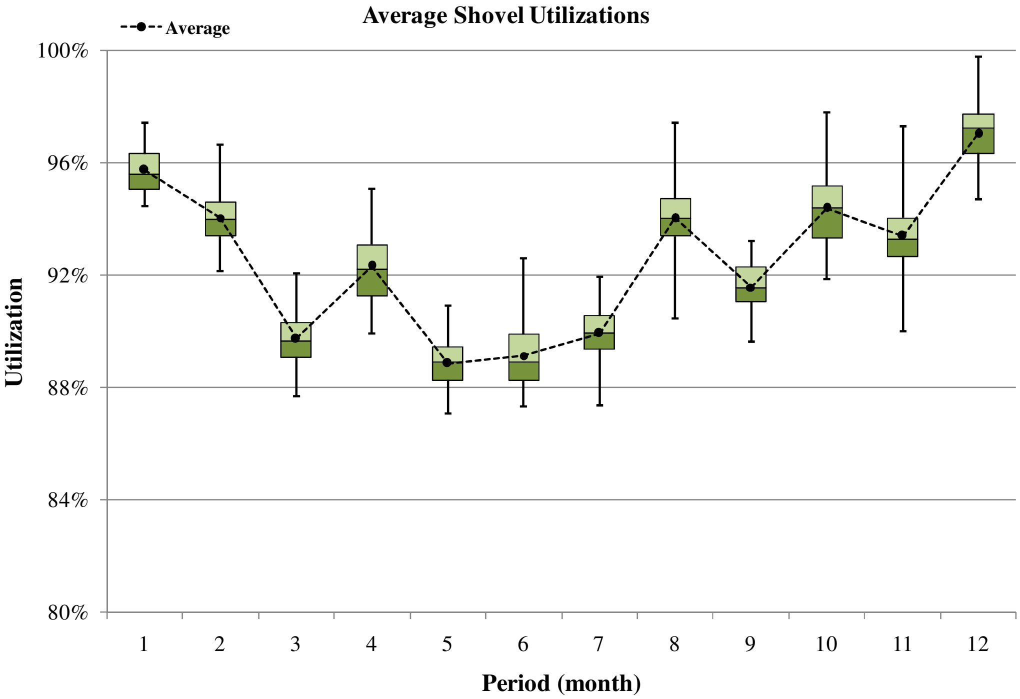

Figure 15. Box plot of average shovel utilization during each period

Table 9. Statistics of average shovel utilization during each period

Month	Minimum (%)	1st Quartile (%)	Median (%)	3rd Quartile (%)	Maximum (%)	Average (%)
1	94.46	95.04	95.59	96.31	97.43	95.74
2	92.15	93.39	93.98	94.62	96.63	94.03
3	87.67	89.08	89.65	90.29	92.06	89.73
4	89.91	91.26	92.21	93.09	95.08	92.32
5	87.08	88.26	88.91	89.43	90.92	88.86
6	87.32	88.24	88.92	89.88	92.58	89.13
7	87.37	89.37	89.94	90.55	91.95	89.93
8	90.47	93.40	94.00	94.72	97.41	94.02
9	89.64	91.07	91.53	92.28	93.20	91.56
10	91.85	93.34	94.40	95.19	97.77	94.38
11	90.00	92.67	93.28	94.02	97.31	93.40
12	94.69	96.34	97.23	97.72	99.78	97.03

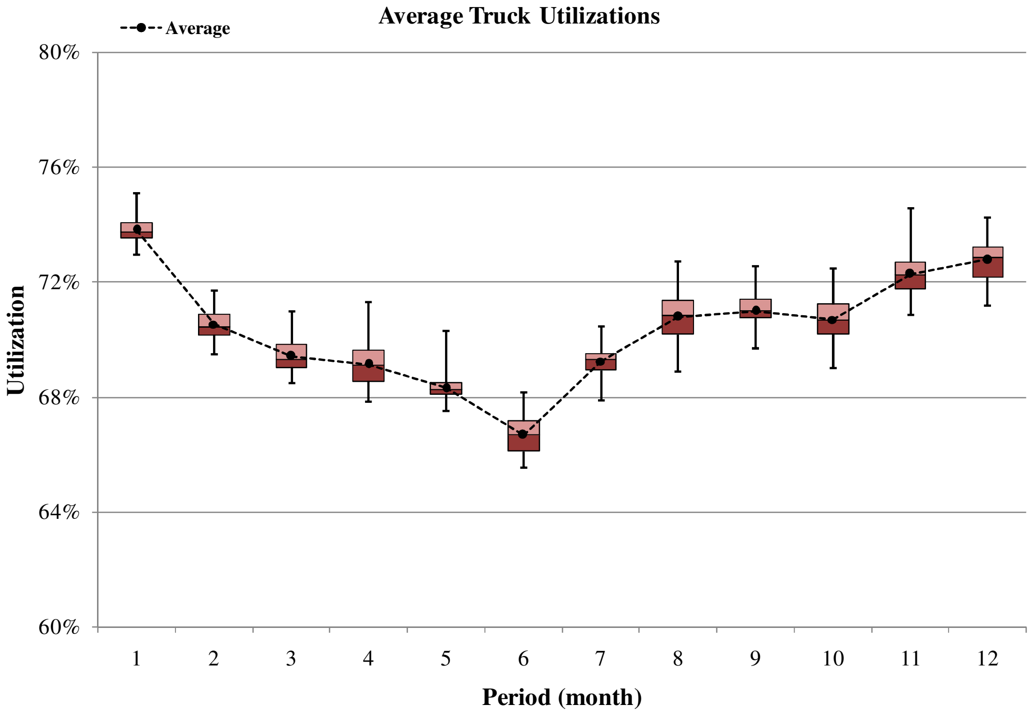

Figure 16. Box plot of average truck utilization during each period

Table 10. Statistics of average truck utilization during each period

Month	Minimum (%)	1st Quartile (%)	Median (%)	3rd Quartile (%)	Maximum (%)	Average (%)
1	72.97	73.54	73.72	74.06	75.10	73.81
2	69.50	70.17	70.43	70.88	71.71	70.52
3	68.47	69.02	69.29	69.84	70.96	69.42
4	67.82	68.55	69.12	69.62	71.31	69.14
5	67.49	68.08	68.26	68.48	70.30	68.30
6	65.52	66.11	66.68	67.16	68.16	66.68
7	67.86	68.94	69.30	69.52	70.45	69.23
8	68.89	70.19	70.82	71.36	72.73	70.78
9	69.67	70.74	70.98	71.41	72.54	70.98
10	69.02	70.19	70.66	71.23	72.48	70.69
11	70.85	71.76	72.26	72.68	74.58	72.28
12	71.17	72.15	72.83	73.20	74.26	72.78

Delivered material tonnage is another significant KPI which is also used to verify the model. Total delivered material tonnage to different destinations should follow the optimal short-term prodction schedule. There are some abrevations in the following figures and tables which are:

- PR1: Material delivered directly from the mine to processing plant 1.
- PR2:Material delivered directly from the mine to processing plant 2.
- SP1:Material delivered to stockpile 1.
- SP2:Material delivered to stockpile 2.
- SP1 to PR1: Material reclaimed from stockpile 1 and delivered to processing plant 1.
- SP2 to PR2:Material reclaimed from stockpile 2 and delivered to processing plant 2.
- WD1:Material delivered to waste dump 1.
- WD2:Material delivered to waste dump 2.

Because no material is delivered to waste dump 2, this destination is not shown in any of the charts. This is because waste dump 1 is nearer to the pit-exit point and has an unlimited capacity, so all waste material is delivered to waste dump 1. Although there are stochastic variables associated with truck-and-shovel operations, the total delivered material tonnage to the destinations is consistent in different replications, as shown in Figure 17 and Table 11. Comparing Figure 17 to Figure 9 shows that the designed truck-and-shovel system delivers the target ore tonnage of 0.64 million tonnes per month.

Having an invariable feed of material at the end of a period in different replications occurs because the numbers of trucks and shovels has been determined in such a way as to meet the production target. If the production target in any of the replications is not met, the number of trucks or shovels should be increased by assessing alternative scenarios.

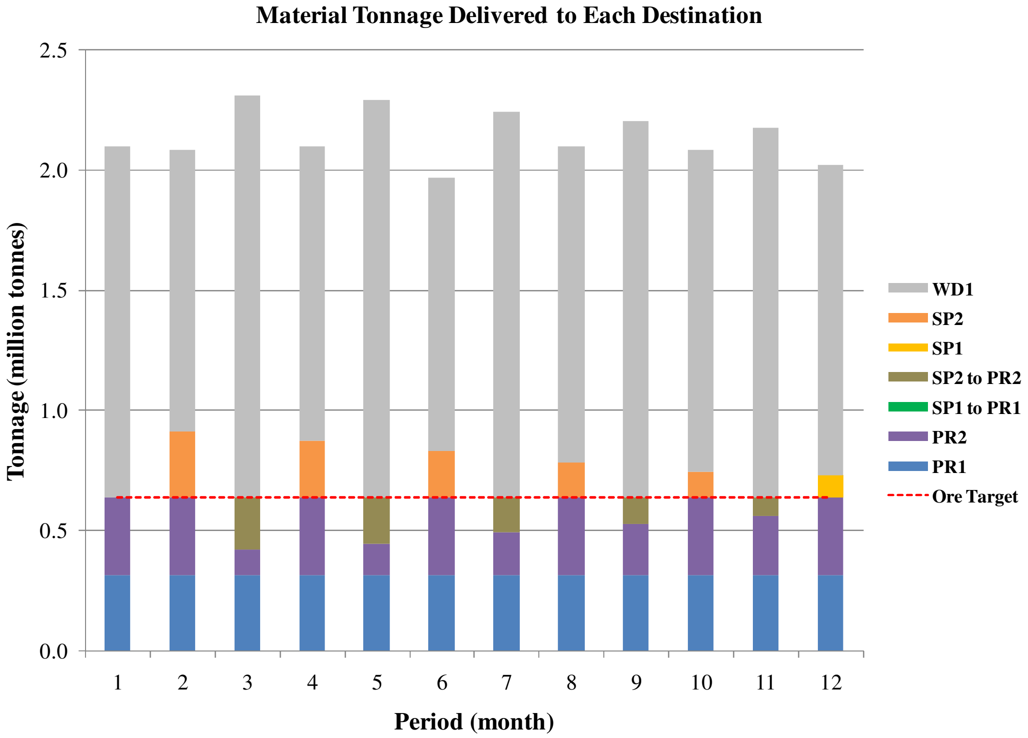

Figure 17. Delivered material tonnage to different destinations

Table 11. Material tonnage delivered to different destinations (million tonnes)

Month	PR1	PR2	SP1 to PR1	SP2 to PR2	SP1	SP2	WD1
1	0.32	0.32	0.00	0.00	0.00	0.00	1.46
2	0.32	0.32	0.00	0.00	0.00	0.28	1.17
3	0.32	0.11	0.00	0.21	0.00	0.00	1.67
4	0.32	0.32	0.00	0.00	0.00	0.24	1.22
5	0.32	0.13	0.00	0.19	0.00	0.00	1.65
6	0.32	0.32	0.00	0.00	0.00	0.19	1.14
7	0.32	0.17	0.00	0.15	0.00	0.00	1.61
8	0.32	0.32	0.00	0.00	0.00	0.15	1.31
9	0.32	0.21	0.00	0.11	0.00	0.00	1.57
10	0.32	0.32	0.00	0.00	0.00	0.11	1.34
11	0.32	0.24	0.00	0.08	0.00	0.00	1.54
12	0.32	0.32	0.00	0.00	0.09	0.00	1.29

As explained before, grades of elements such as iron, phosphor, and sulfur are taken into consideration. Figure 18, Figure 19, and Figure 20, respectively, show the weighted average grade of iron, phosphor and sulfur of the material delivered to different destinations. Because the delivered material tonnage do not vary, the grades do not differ in different replications. Although there are some variations from one period to another, all grades are between the predetermined boundaries (compare Table 12, Table 13, and Table 14 to Table 1). This further confirms that the model is working accurately.

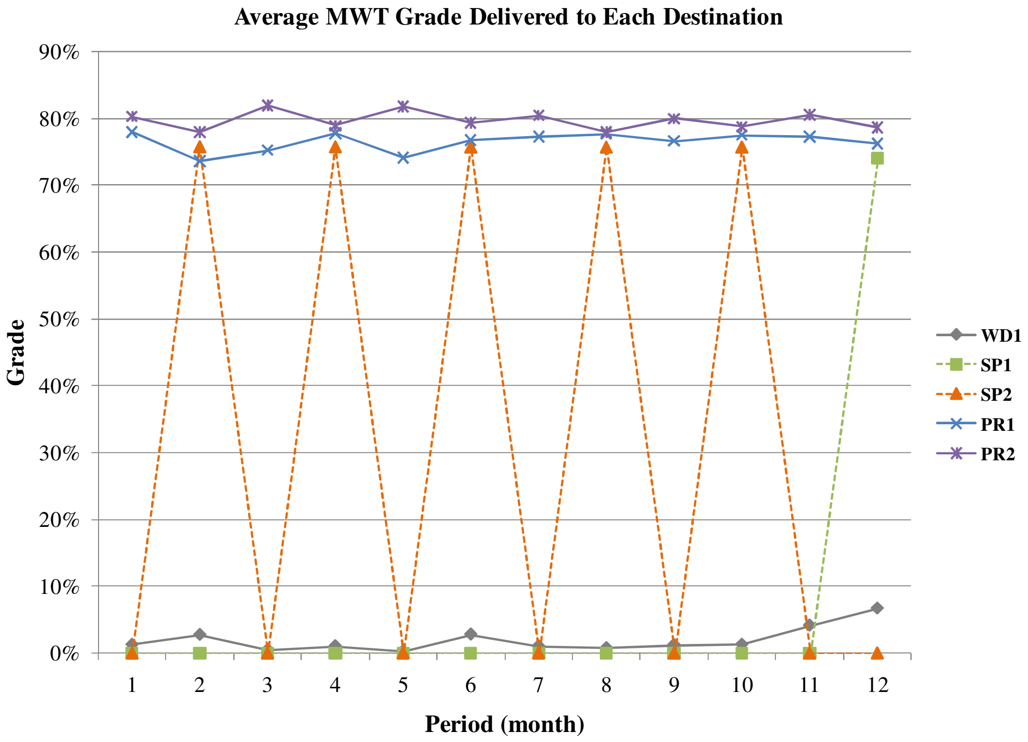

Figure 18. Average MWT grade of material delivered to different destinations

Table 12. Average MWT grade of material delivered to different destinations (%)

Month	PR1	PR2	SP1	SP2	WD1
1	78.00	80.30	0.00	0.00	1.28
2	73.70	78.00	0.00	75.78	2.78
3	75.32	82.00	0.00	0.00	0.51
4	77.79	78.96	0.00	75.80	1.07
5	74.27	81.80	0.00	0.00	0.31
6	76.75	79.40	0.00	75.76	2.83
7	77.28	80.50	0.00	0.00	1.05
8	77.72	78.00	0.00	75.74	0.76
9	76.67	80.00	0.00	0.00	1.26
10	77.53	78.80	0.00	75.72	1.29
11	77.32	80.60	0.00	0.00	4.19
12	76.25	78.70	74.00	0.00	6.77

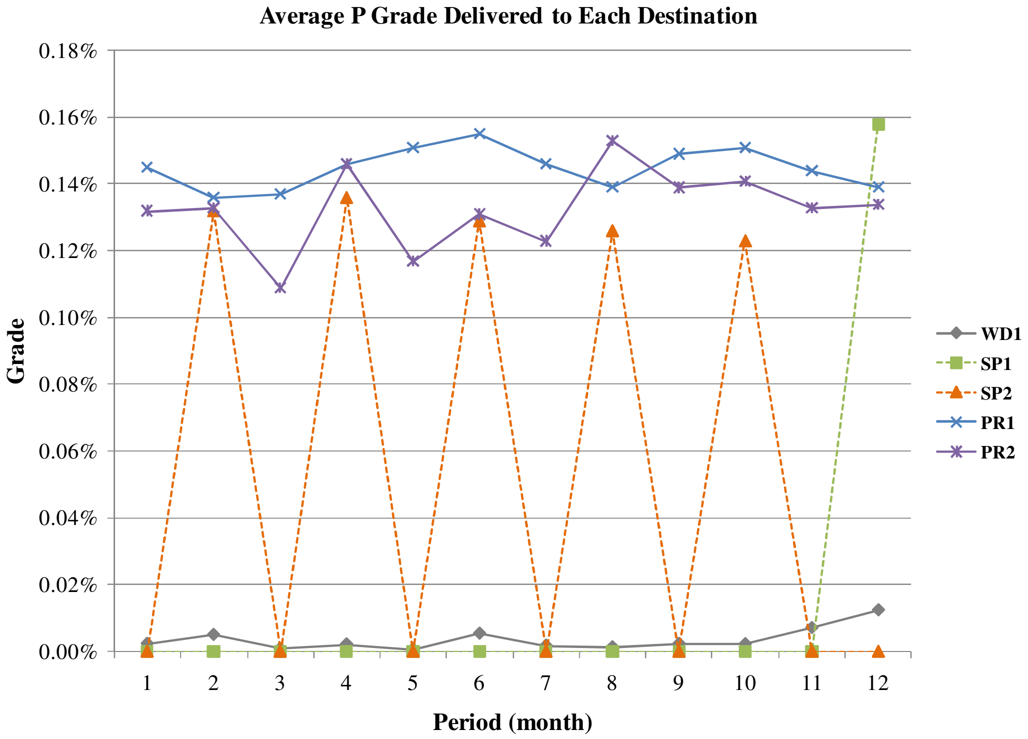

Figure 19. Average phosphor grade of material delivered to different destinations

Table 13. Average phosphor grade of material delivered to different destinations (%)

Month	PR1	PR2	SP1	SP2	WD1
1	0.15	0.13	0.00	0.00	0.00
2	0.14	0.13	0.00	0.13	0.01
3	0.14	0.11	0.00	0.00	0.00
4	0.15	0.15	0.00	0.14	0.00
5	0.15	0.12	0.00	0.00	0.00
6	0.16	0.13	0.00	0.13	0.01
7	0.15	0.12	0.00	0.00	0.00
8	0.14	0.15	0.00	0.13	0.00
9	0.15	0.14	0.00	0.00	0.00
10	0.15	0.14	0.00	0.12	0.00
11	0.14	0.13	0.00	0.00	0.01
12	0.14	0.13	0.16	0.00	0.01

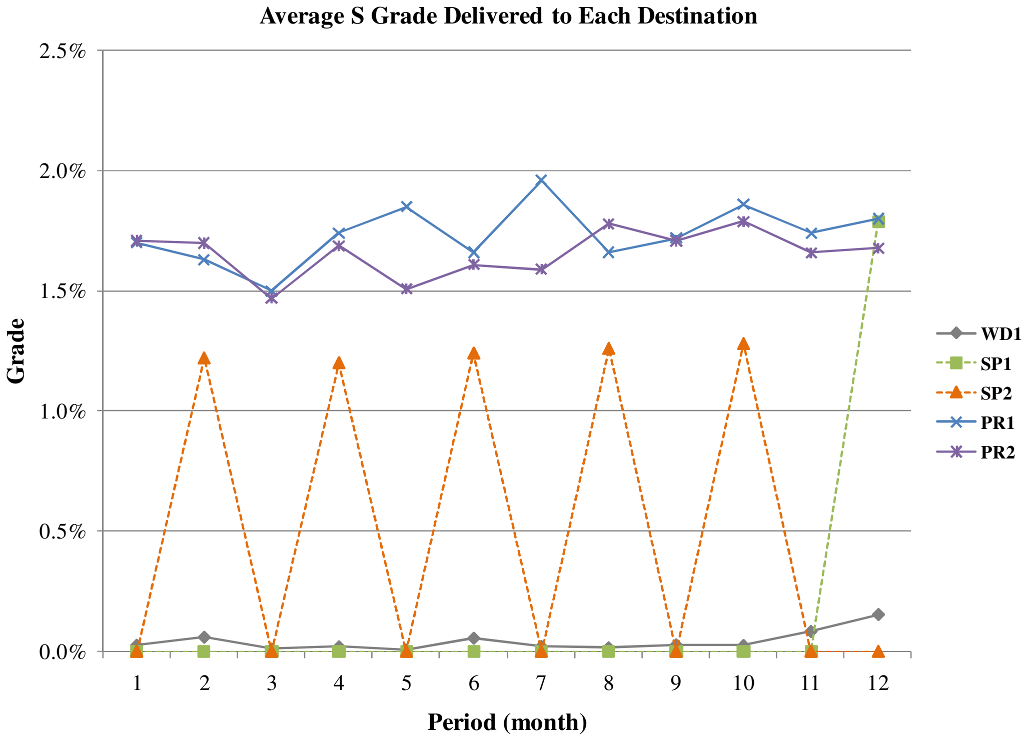

Figure 20. Average sulfur grade of material delivered to different destinations

Table 14. Average sulfur grade of material delivered to different destinations (%)

Month	PR1	PR2	SP1	SP2	WD1
1	1.70	1.71	0.00	0.00	0.03
2	1.63	1.70	0.00	1.22	0.06
3	1.50	1.47	0.00	0.00	0.01
4	1.74	1.69	0.00	1.20	0.02
5	1.85	1.51	0.00	0.00	0.01
6	1.66	1.61	0.00	1.24	0.06
7	1.96	1.59	0.00	0.00	0.02
8	1.66	1.78	0.00	1.26	0.02
9	1.72	1.71	0.00	0.00	0.03
10	1.86	1.79	0.00	1.28	0.03
11	1.74	1.66	0.00	0.00	0.08
12	1.80	1.68	1.79	0.00	0.15

The waiting time at different destinations is one of the main KPIs that shows how effectively the trucks are used. Truck waiting times show how much time a truck waits at a destination for the facility at that destination to become available. Shorter waiting times mean equipment is operating effectively. The destination facility may be unavailable due to two reasons:

1. Other trucks are dumping at the destination and there is no room for the truck to dump its load, because a limited number of trucks can dump simultaneously at each of the destinations.
2. The destination facility has failed.

As can be seen from Figure 21 and Table 15, most truck waiting times occur at processing plants. Trucks do not wait at the other destinations, because there is no failure at waste dumps and stockpiles. Another reason that trucks don’t wait at waste dumps is that there is room for three trucks at a waste dump, whereas there is room for only one truck at each of the processing plants.

Box plots shown in Figure 21 are the average waiting time throughout the year. Because the average waiting times at processing plant 1 and 2 are high (around 2.25 minutes), this KPI is monitored during each month for these two destinations. Resulting average truck waiting times at processing plant 1 and 2 are presented in Figure 22 and Figure 23, and the corresponding statistics are indicated in Table 16 and Table 17, respectively.

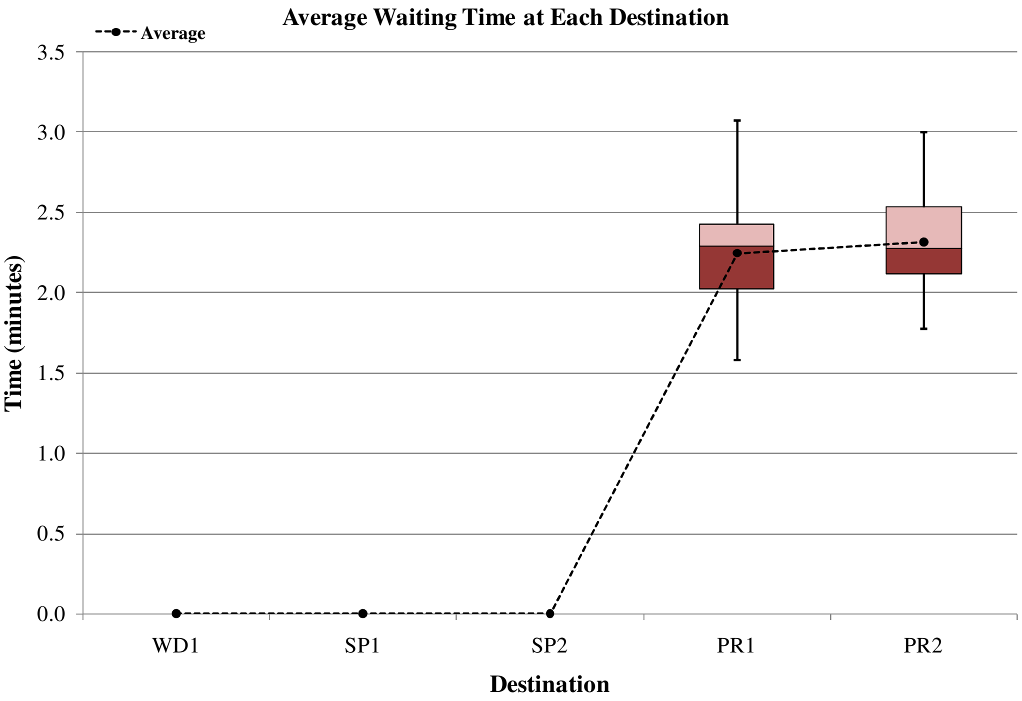

Figure 21. Average truck waiting time at each destination

Table 15. Statistics of average truck waiting time at each destination

Destination	Minimum (min)	1st Quartile (min)	Median (min)	3rd Quartile (min)	Maximum (min)	Average (min)
WD1	0.00	0.00	0.00	0.00	0.00	0.00
SP1	0.00	0.00	0.00	0.00	0.00	0.00
SP2	0.00	0.00	0.00	0.00	0.00	0.00
PR1	1.58	2.02	2.29	2.43	3.07	2.25
PR2	1.78	2.12	2.28	2.53	3.00	2.32

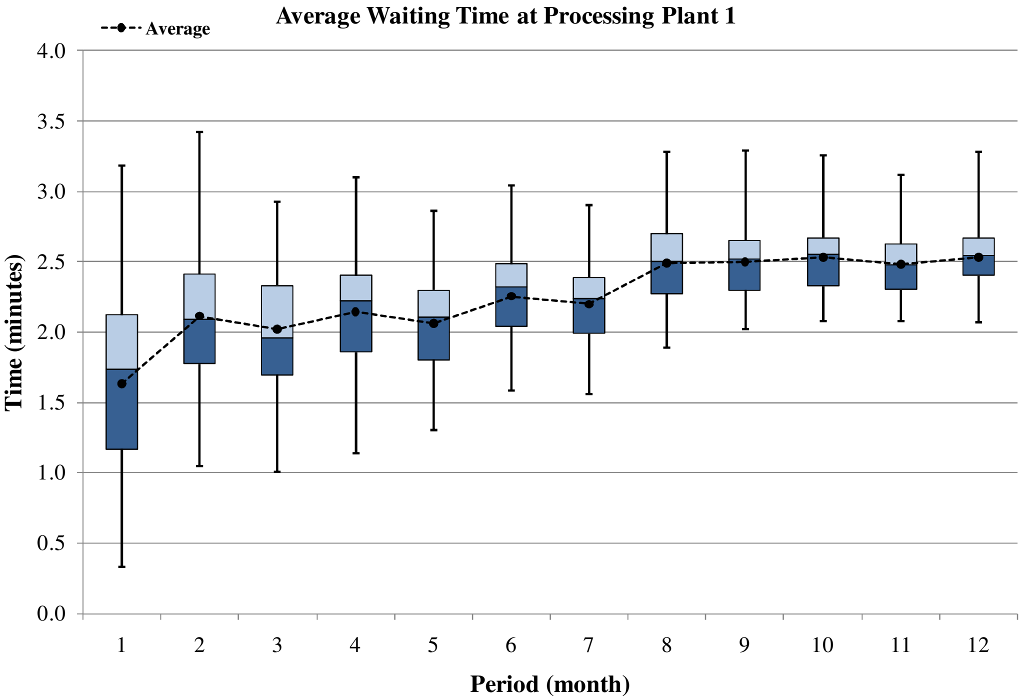

Figure 22. Average truck waiting time at processing plant 1

Table 16. Statistics of average truck waiting time at processing plant 1

Month	Minimum (min)	1st Quartile (min)	Median (min)	3rd Quartile (min)	Maximum (min)	Average (min)
1	0.33	1.17	1.74	2.12	3.18	1.63
2	1.05	1.78	2.09	2.41	3.42	2.11
3	1.01	1.70	1.96	2.33	2.93	2.02
4	1.14	1.86	2.22	2.40	3.10	2.14
5	1.30	1.80	2.11	2.30	2.86	2.06
6	1.58	2.04	2.32	2.48	3.04	2.25
7	1.56	1.99	2.24	2.39	2.90	2.20
8	1.89	2.27	2.50	2.70	3.28	2.49
9	2.02	2.30	2.52	2.65	3.29	2.50
10	2.08	2.33	2.56	2.67	3.26	2.53
11	2.08	2.30	2.48	2.62	3.12	2.48
12	2.07	2.40	2.54	2.67	3.28	2.53

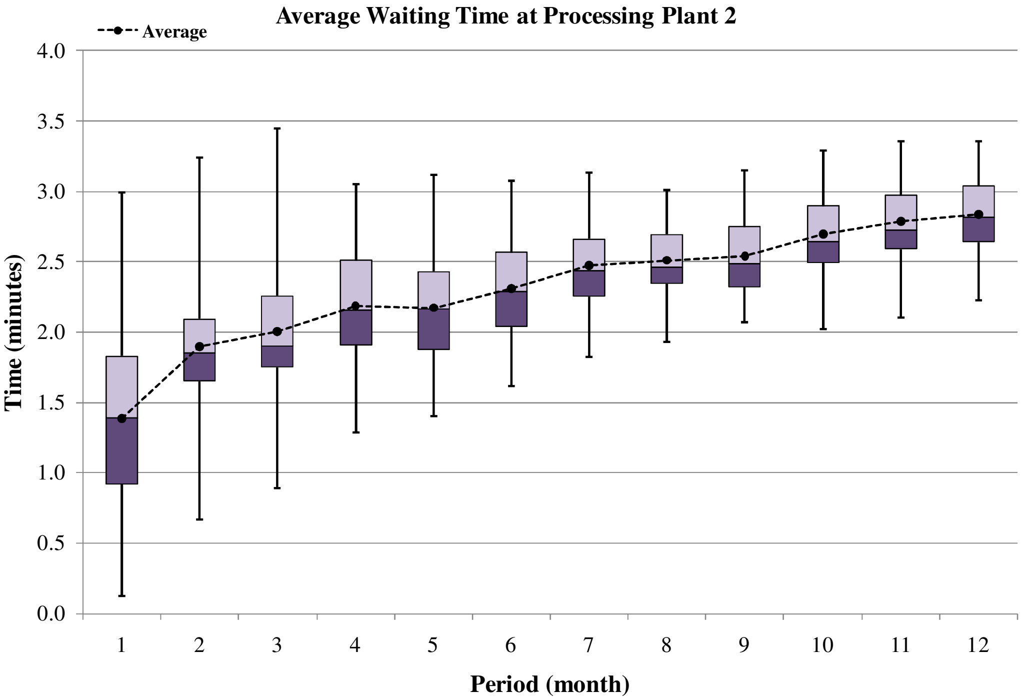

Figure 23. Average truck waiting time at processing plant 2

Table 17. Statistics of average truck waiting time at processing plant 2

Month	Minimum (min)	1st Quartile (min)	Median (min)	3rd Quartile (min)	Maximum (min)	Average (min)
1	0.12	0.92	1.39	1.83	2.99	1.39
2	0.67	1.65	1.86	2.09	3.24	1.90
3	0.89	1.75	1.91	2.26	3.45	2.00
4	1.29	1.91	2.16	2.51	3.05	2.19
5	1.40	1.88	2.17	2.43	3.12	2.17
6	1.62	2.04	2.29	2.57	3.08	2.31
7	1.82	2.25	2.44	2.66	3.13	2.47
8	1.93	2.34	2.47	2.70	3.01	2.51
9	2.07	2.33	2.49	2.75	3.15	2.54
10	2.02	2.49	2.64	2.90	3.29	2.70
11	2.10	2.59	2.73	2.97	3.36	2.79
12	2.23	2.64	2.82	3.04	3.36	2.84

Another important KPI regarding the queues formed at different destinations is the queue length. The box plots of average queue lengths at each of the destinations are shown in Figure 24 with the statistics in Table 18. Because the waiting time at processing plants 1 and 2 are higher, the queue lengths are also higher in these destinations compared to other destinations. The detailed box plots of average monthly queue length at these destinations are demonstrated in Figure 25 and Figure 26, and the corresponding data are presented inTable 19 and Table 20, respectively.

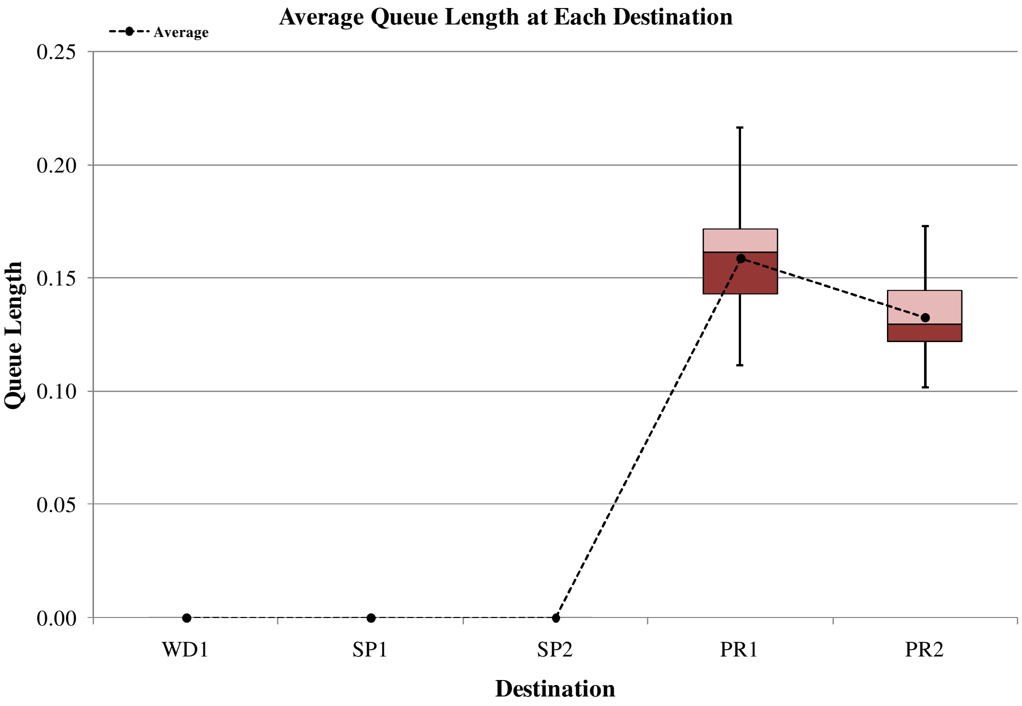

Figure 24. Average queue length at each destination

Table 18. Statistics of average queue length at each destination

Destination	Minimum	1st Quartile	Median	3rd Quartile	Maximum	Average
WD1	0.00	0.00	0.00	0.00	0.00	0.00
SP1	0.00	0.00	0.00	0.00	0.00	0.00
SP2	0.00	0.00	0.00	0.00	0.00	0.00
PR1	0.11	0.14	0.16	0.17	0.22	0.16
PR2	0.10	0.12	0.13	0.14	0.17	0.13

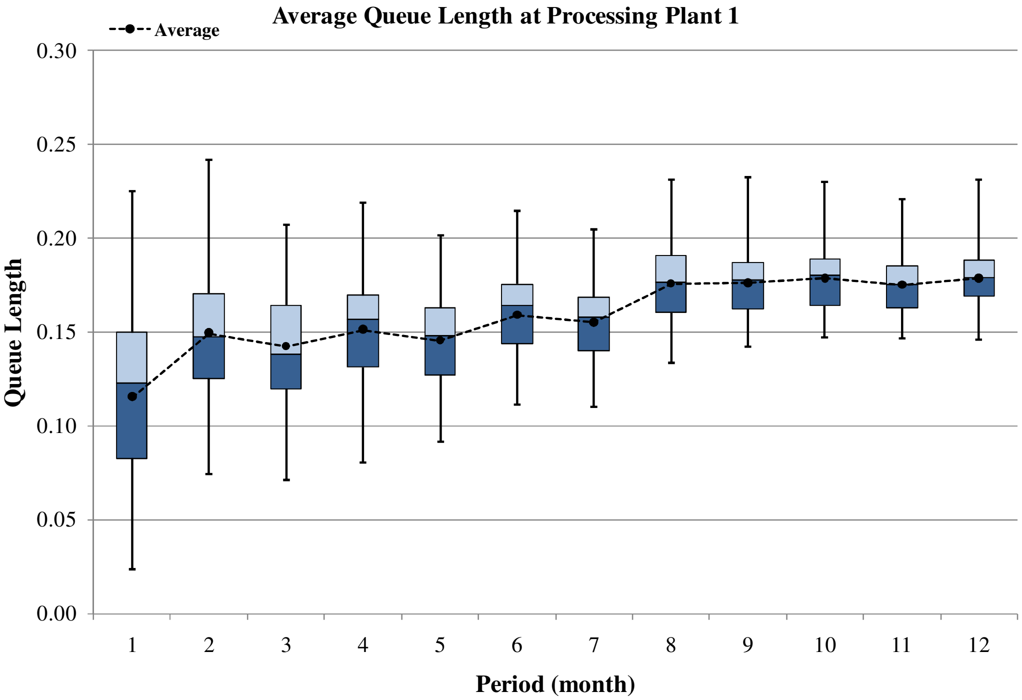

Figure 25. Average queue length at processing plant 1

Table 19. Statistics of average queue length at processing plant 1

Month	Minimum	1^{st} Quartile	Median	3^{rd} Quartile	Maximum	Average
1	0.02	0.08	0.12	0.15	0.23	0.12
2	0.07	0.13	0.15	0.17	0.24	0.15
3	0.07	0.12	0.14	0.16	0.21	0.14
4	0.08	0.13	0.16	0.17	0.22	0.15
5	0.09	0.13	0.15	0.16	0.20	0.15
6	0.11	0.14	0.16	0.18	0.21	0.16
7	0.11	0.14	0.16	0.17	0.20	0.16
8	0.13	0.16	0.18	0.19	0.23	0.18
9	0.14	0.16	0.18	0.19	0.23	0.18
10	0.15	0.16	0.18	0.19	0.23	0.18
11	0.15	0.16	0.18	0.18	0.22	0.18
12	0.15	0.17	0.18	0.19	0.23	0.18

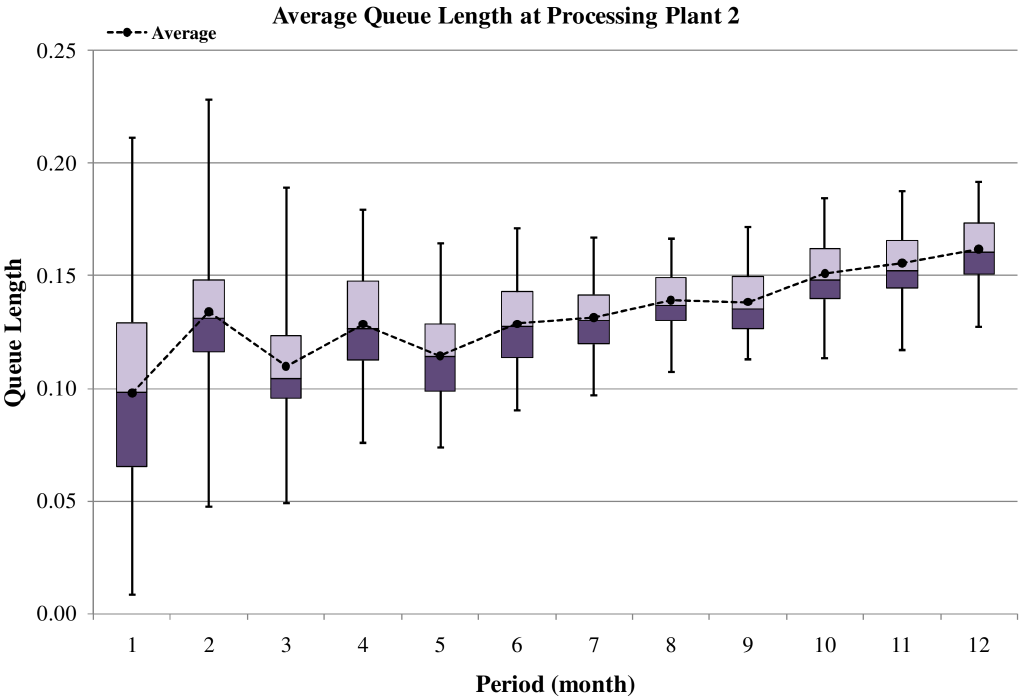

Figure 26. Average queue length at processing plant 2

Table 20. statistics of average queue length at processing plant 2

Month	Minimum	1st Quartile	Median	3rd Quartile	Maximum	Average
1	0.01	0.07	0.10	0.13	0.21	0.10
2	0.05	0.12	0.13	0.15	0.23	0.13
3	0.05	0.10	0.10	0.12	0.19	0.11
4	0.08	0.11	0.13	0.15	0.18	0.13
5	0.07	0.10	0.11	0.13	0.16	0.11
6	0.09	0.11	0.13	0.14	0.17	0.13
7	0.10	0.12	0.13	0.14	0.17	0.13
8	0.11	0.13	0.14	0.15	0.17	0.14
9	0.11	0.13	0.14	0.15	0.17	0.14
10	0.11	0.14	0.15	0.16	0.18	0.15
11	0.12	0.14	0.15	0.17	0.19	0.16
12	0.13	0.15	0.16	0.17	0.19	0.16

All the results presented are based on the monthly analysis of the system, because the optimal short-term schedule is monthly-based. This research goes beyond the monthly assessment of the system, and looks into some KPIs in more detail during each shift. As the primary KPI, delivered total material tonnage is evaluated during each shift. For this purpose 10 consecutive days consisting of 10 day shifts and 10 night shifts are chosen.

The shift-based box plots and statistics of aforementioned KPI are shown in Figure 27 and Table 21, respectively. Although the monthly material tonnage has not deviated from the monthly production target, the shift-based material tonnage shows some variations. The shift-based production should be around 36.67 thousand tonnes, a calculation that is obtained in the following manner:

$$\begin{aligned} \textit{shift-based production target} &= \frac{\textit{monthly production target}}{\textit{number of shifts in a month}} \\ &= \frac{2.2 \ \textit{(million tonnes)}}{30 \ \textit{(days)} \times 2 \ \textit{(shifts)}} \\ &= 36.67 \ \textit{(thousand tonnes)} \end{aligned}$$

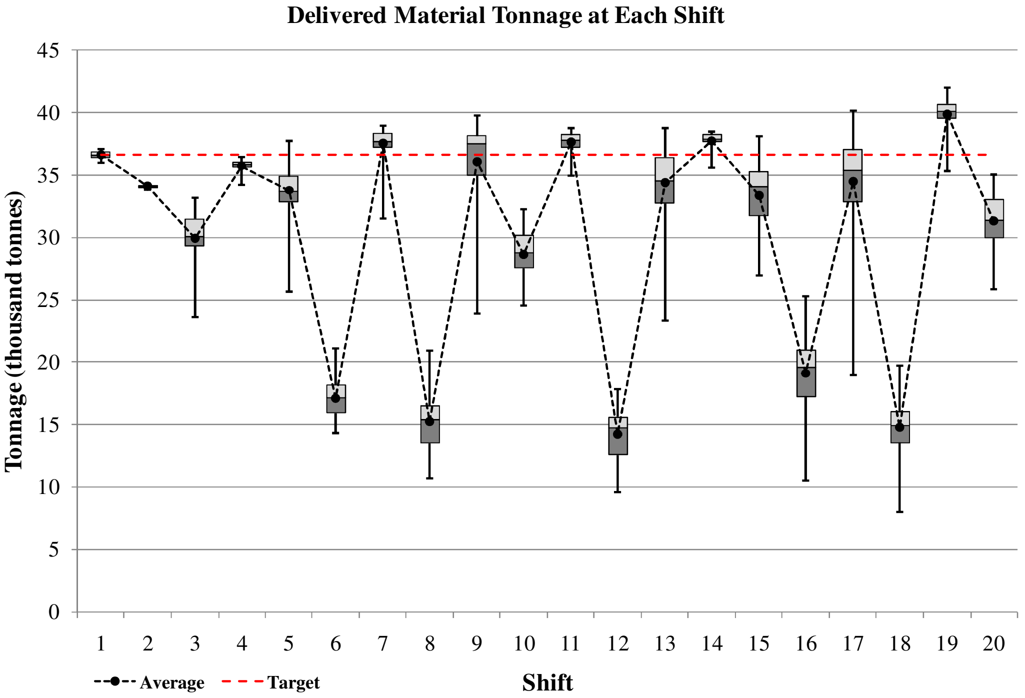

Figure 27. Box plot of delivered material tonnage during sample shifts

Table 21. Statistics of delivered material tonnage during sample shifts (thousand tonnes)

Month	Minimum	1st Quartile	Median	3rd Quartile	Maximum	Average
1	35.99	36.40	36.55	36.80	37.13	36.59
2	33.88	34.01	34.08	34.16	34.33	34.08
3	23.62	29.30	30.10	31.49	33.19	29.93
4	34.23	35.65	35.84	36.00	36.41	35.73
5	25.66	32.83	33.72	34.90	37.77	33.78
6	14.36	15.95	17.16	18.22	21.13	17.14
7	31.48	37.17	37.71	38.35	39.00	37.56
8	10.74	13.51	15.39	16.48	20.97	15.31
9	23.88	34.97	37.46	38.11	39.82	36.06
10	24.56	27.51	28.81	30.12	32.28	28.66
11	34.93	37.24	37.80	38.23	38.80	37.61
12	9.59	12.60	14.79	15.63	17.86	14.25
13	23.33	32.71	34.52	36.41	38.73	34.39
14	35.60	37.67	37.86	38.18	38.46	37.74
15	26.96	31.75	34.03	35.27	38.12	33.37
16	10.54	17.25	19.54	21.00	25.32	19.14
17	18.98	32.88	35.32	37.00	40.18	34.47
18	8.01	13.58	14.95	16.02	19.70	14.82
19	35.35	39.56	40.09	40.67	42.00	39.88
20	25.86	29.97	31.34	33.06	35.05	31.34

These variations in the shift-based production level occur mainly because of the failures of trucks, shovels, and crushers. Therefore, it is very important to evaluate these stochastic variables during each shift. For this purpose, the same 10 days are considered, and the average duration of failure for a truck, shovel, and crusher are assessed.

The results are summarized using box plots, for which the corresponding statistics are presented in Table 22, Table 23, and Table 24. Reviewing Figure 28, Figure 29, and Figure 30 with Figure 27 shows that during shifts when the production level is much lower than the target, the failure duration of a truck, shovel, crusher, or any combination of the three is higher. For instance, the average failure durations of trucks and shovels are higher during shift 12, and accordingly production level is very low in this shift. The other example is shift 16, in which the low production level is caused by truck and crusher failures.

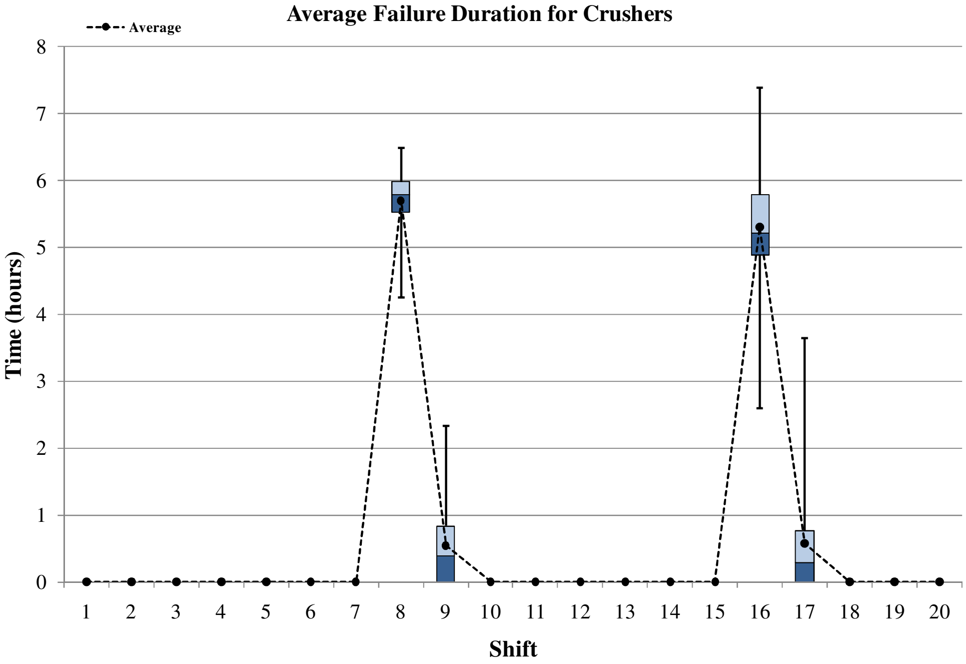

Figure 28. Box plot of average failure duration for crushers during sample shifts

Table 22. Statistics of average failure duration for crushers during sample shifts

Month	Minimum (h)	1^{st} Quartile (h)	Median (h)	3^{rd} Quartile (h)	Maximum (h)	Average (h)
1	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00	0.00
8	4.26	5.53	5.79	5.99	6.48	5.70
9	0.00	0.01	0.39	0.84	2.34	0.55
10	0.00	0.00	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00	0.00
16	2.60	4.89	5.21	5.78	7.39	5.30
17	0.00	0.00	0.30	0.76	3.64	0.57
18	0.00	0.00	0.00	0.00	0.00	0.00
19	0.00	0.00	0.00	0.00	0.00	0.00
20	0.00	0.00	0.00	0.00	0.00	0.00

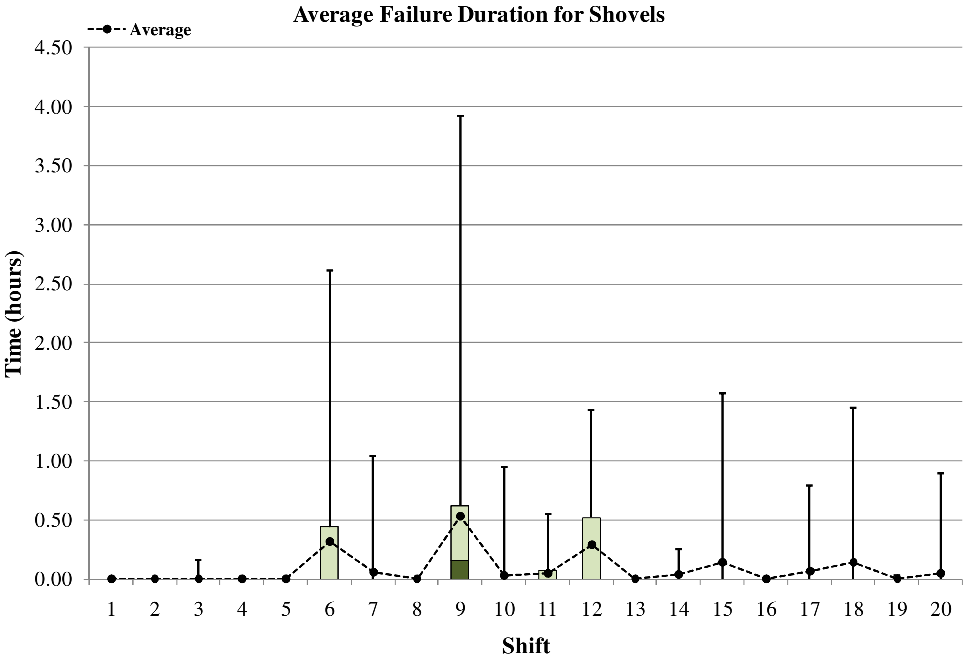

Figure 29. Box plot of average failure duration for shovels during sample shifts

Table 23. Statistics of average failure duration for shovels during sample shifts

Month	Minimum (h)	1st Quartile (h)	Median (h)	3rd Quartile (h)	Maximum (h)	Average (h)
1	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00	0.16	0.00
4	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.44	2.61	0.31
7	0.00	0.00	0.00	0.00	1.04	0.06
8	0.00	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.15	0.62	3.92	0.53
10	0.00	0.00	0.00	0.00	0.95	0.03
11	0.00	0.00	0.00	0.07	0.55	0.05
12	0.00	0.00	0.00	0.52	1.43	0.29
13	0.00	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.25	0.04
15	0.00	0.00	0.00	0.00	1.57	0.14
16	0.00	0.00	0.00	0.00	0.00	0.00
17	0.00	0.00	0.00	0.00	0.79	0.06
18	0.00	0.00	0.00	0.00	1.45	0.14
19	0.00	0.00	0.00	0.00	0.03	0.00
20	0.00	0.00	0.00	0.00	0.90	0.05

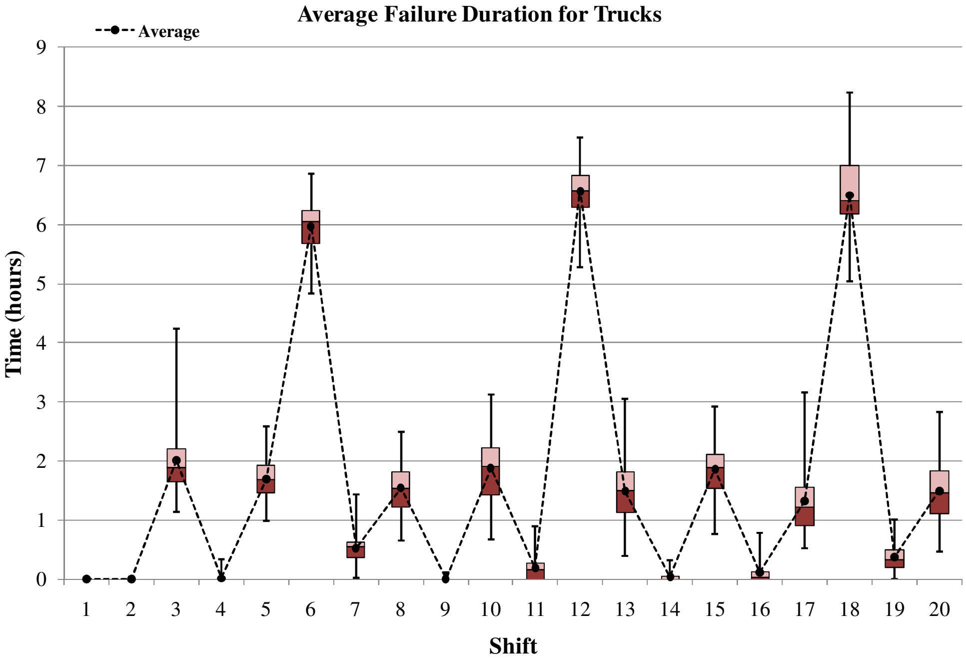

Figure 30. Box plot of average failure duration for trucks during sample shifts

Table 24. Statistics of average failure duration for trucks during sample shifts

Month	Minimum (h)	1st Quartile (h)	Median (h)	3rd Quartile (h)	Maximum (h)	Average (h)
1	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00
3	1.13	1.66	1.90	2.21	4.24	2.01
4	0.00	0.00	0.00	0.00	0.33	0.01
5	0.99	1.46	1.68	1.93	2.58	1.70
6	4.84	5.68	6.06	6.23	6.87	5.97
7	0.03	0.37	0.55	0.63	1.43	0.53
8	0.66	1.22	1.53	1.81	2.49	1.55
9	0.00	0.00	0.00	0.00	0.11	0.01
10	0.68	1.44	1.92	2.23	3.12	1.88
11	0.00	0.00	0.17	0.27	0.90	0.18
12	5.28	6.29	6.58	6.83	7.48	6.58
13	0.40	1.14	1.50	1.81	3.06	1.49
14	0.00	0.00	0.00	0.06	0.32	0.04
15	0.77	1.53	1.90	2.12	2.92	1.86
16	0.00	0.00	0.05	0.14	0.78	0.12
17	0.52	0.91	1.22	1.56	3.16	1.32
18	5.03	6.18	6.40	7.00	8.23	6.51
19	0.00	0.20	0.33	0.50	1.00	0.38
20	0.48	1.11	1.47	1.84	2.82	1.50

Truck cycle time is another critical KPI that is addressed in this section. The main stochastic variables that affect the truck cycle time are the velocities of trucks and shovels. Because the velocities of trucks and shovels differ during day and night shifts, the average truck cycle times during day and night shifts are assessed in detail.

For this purpose, the time span of a shift is considered through the whole year, not just the sample 10 days. Figure 31 and Figure 32 (correspondingly Table 25 and Table 26) show the variations in shift-based truck cycle time during different months.

In addition to Figure 31 and Figure 32 that show the details of shift-based truck cycle times during different months, Figure 33 shows a bigger picture comparing the average truck cycle time in day shifts to those in night shifts. Truck cycle time during day shifts is less than that during night shifts because trucks and shovels travel faster during day shifts. The statistics of data that are collected throughout the year are presented in Table 27.

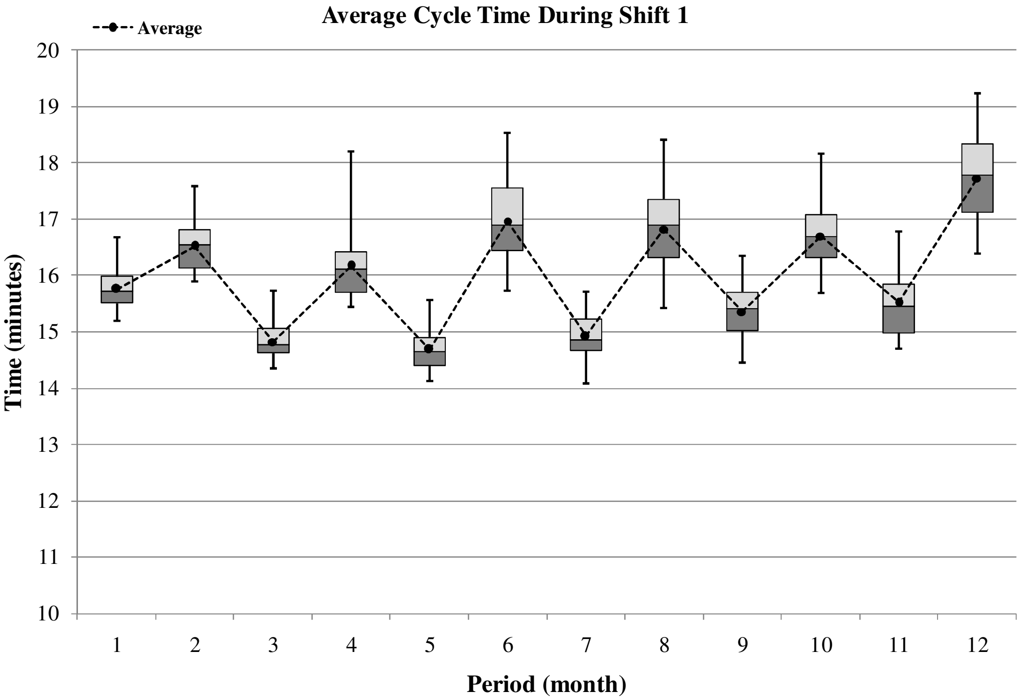

Figure 31. Box plot of average cycle time during day shift

Table 25. Statistics of average cycle time during day shift

Month	Minimum (min)	1st Quartile (min)	Median (min)	3rd Quartile (min)	Maximum (min)	Average (min)
1	15.19	15.51	15.73	15.98	16.68	15.76
2	15.89	16.14	16.55	16.82	17.58	16.52
3	14.34	14.62	14.78	15.06	15.74	14.82
4	15.44	15.71	16.12	16.43	18.21	16.16
5	14.13	14.41	14.65	14.91	15.57	14.68
6	15.74	16.45	16.91	17.55	18.54	16.96
7	14.09	14.68	14.87	15.22	15.71	14.92
8	15.43	16.33	16.90	17.36	18.42	16.82
9	14.46	15.02	15.42	15.70	16.35	15.36
10	15.69	16.33	16.70	17.08	18.17	16.70
11	14.70	14.98	15.46	15.84	16.78	15.52
12	16.39	17.12	17.79	18.34	19.24	17.73

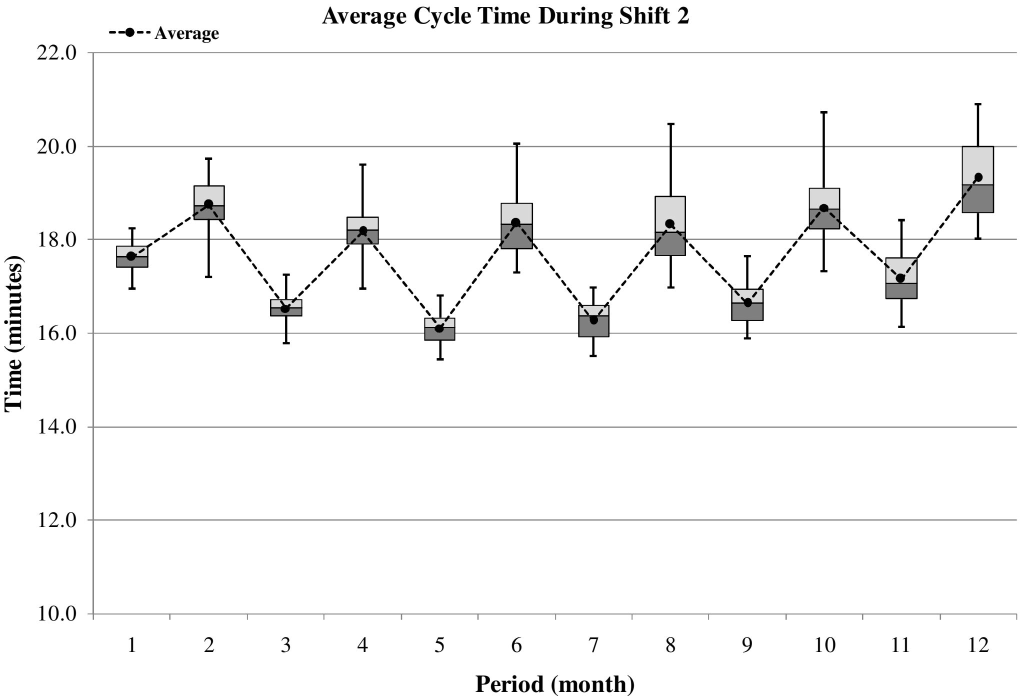

Figure 32. Box plot average cycle time during night shift

Table 26. Statistics of average cycle time during night shift

Month	Minimum (min)	1st Quartile (min)	Median (min)	3rd Quartile (min)	Maximum (min)	Average (min)
1	16.95	17.42	17.63	17.85	18.24	17.63
2	17.20	18.43	18.72	19.14	19.72	18.74
3	15.78	16.38	16.54	16.72	17.25	16.52
4	16.94	17.90	18.19	18.47	19.60	18.17
5	15.43	15.86	16.11	16.33	16.79	16.10
6	17.30	17.81	18.32	18.76	20.05	18.35
7	15.51	15.93	16.36	16.59	16.98	16.27
8	16.97	17.65	18.16	18.92	20.48	18.32
9	15.88	16.27	16.63	16.93	17.65	16.63
10	17.32	18.22	18.66	19.10	20.72	18.68
11	16.13	16.73	17.07	17.60	18.41	17.16
12	18.01	18.56	19.16	19.98	20.90	19.32

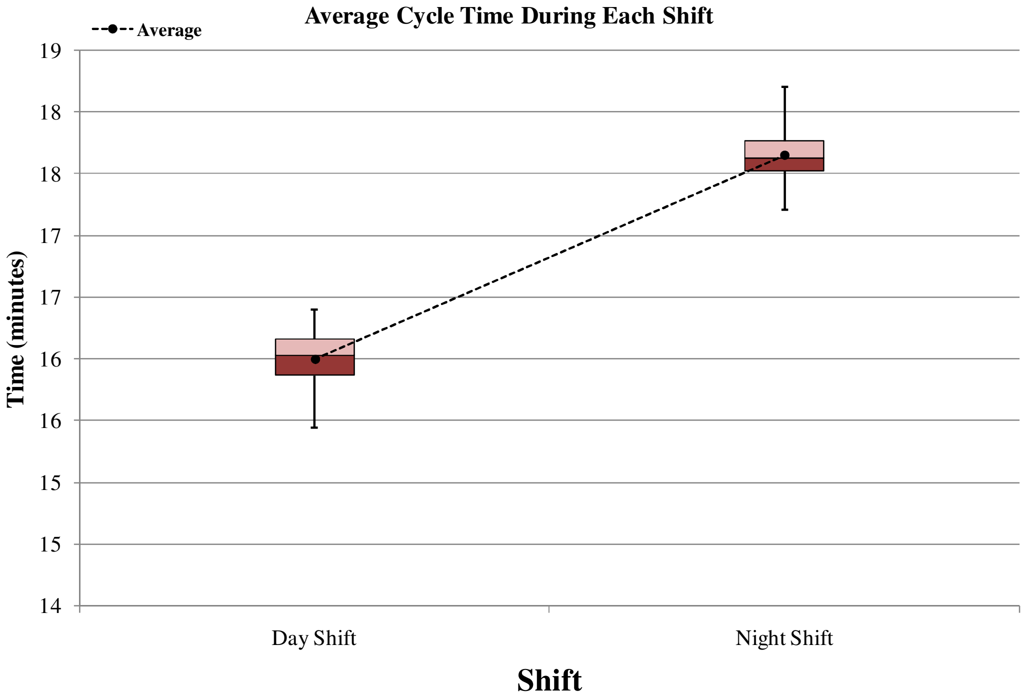

Figure 33. Box plot of average cycle time during each shift

Table 27. Statistics of average cycle time during each shift

Shift	Minimum (min)	1st Quartile (min)	Median (min)	3rd Quartile (min)	Maximum (min)	Average (min)
Day	15.44	15.87	16.03	16.16	16.41	16.00
Night	17.21	17.53	17.62	17.77	18.21	17.66

4.4 Improving the System

As presented in Section 4.3 , trucks wait an average of 2.25 minutes at processing plant 1 and an average of 2.32 minutes at processing plant 2. As also mentioned in Section 4.3, a truck waits for a resource to become available when the resource is either busy or has failed. The largest contributor to truck waiting time is crusher failures. Waiting time occurs because we are following the optimal production schedule, which has been obtained based on a deterministic model. The deterministic production scheduling model assumes that the crusher is available all the time, which is not accurate. So, to have a valid model that can be used as a planning tool, this section adds a more realistic decision-making process to the model. This section tries to improve the current truck-and-shovel system by reducing the truck waiting times at processing plants. For this purpose, it is recommended that if a crusher has failed, no trucks should travel to that processing plant. Instead, trucks should be redirected to the corresponding stockpile. The resulting average waiting time at each destination is presented in Figure 34 and Table 28. In the new scenario, the average waiting times at processing plant 1 and 2 are reduced by more than 99% (see Table 29). The details of monthly average truck waiting times for each of the processing plants are illustrated in Figure 35 and Figure 36. Corresponding statistics are presented in Table 30 and Table 31.

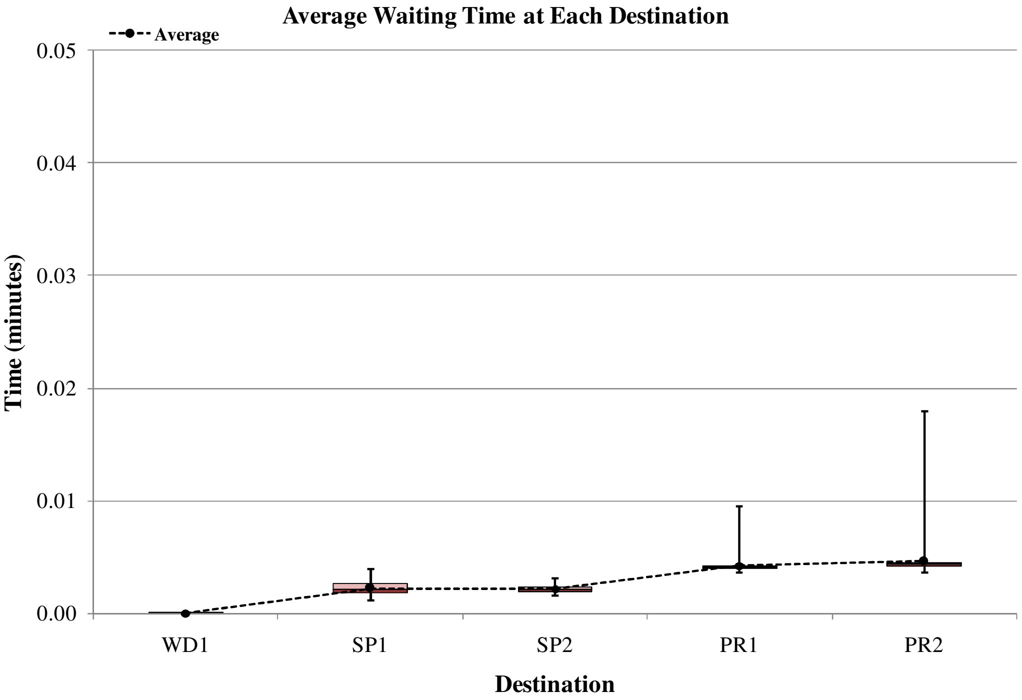

Figure 34. Box plot of average truck waiting time at each destination in new scenario

Table 28. Statistics of average truck waiting time at each destination in new scenario

Destination	Minimum (min)	1st Quartile (min)	Median (min)	3rd Quartile (min)	Maximum (min)	Average (min)
WD1	0.000	0.000	0.000	0.000	0.000	0.000
SP1	0.001	0.002	0.002	0.003	0.004	0.002
SP2	0.002	0.002	0.002	0.002	0.003	0.002
PR1	0.004	0.004	0.004	0.004	0.009	0.004
PR2	0.004	0.004	0.004	0.004	0.018	0.005

Table 29. Improvement percentages in waiting times at processing plants

Destination	Average Waiting time (minute)		Improvement
	Base Scenario	New Scenario	
PR1	2.25	0.004	99.81%
PR2	2.32	0.005	99.80%

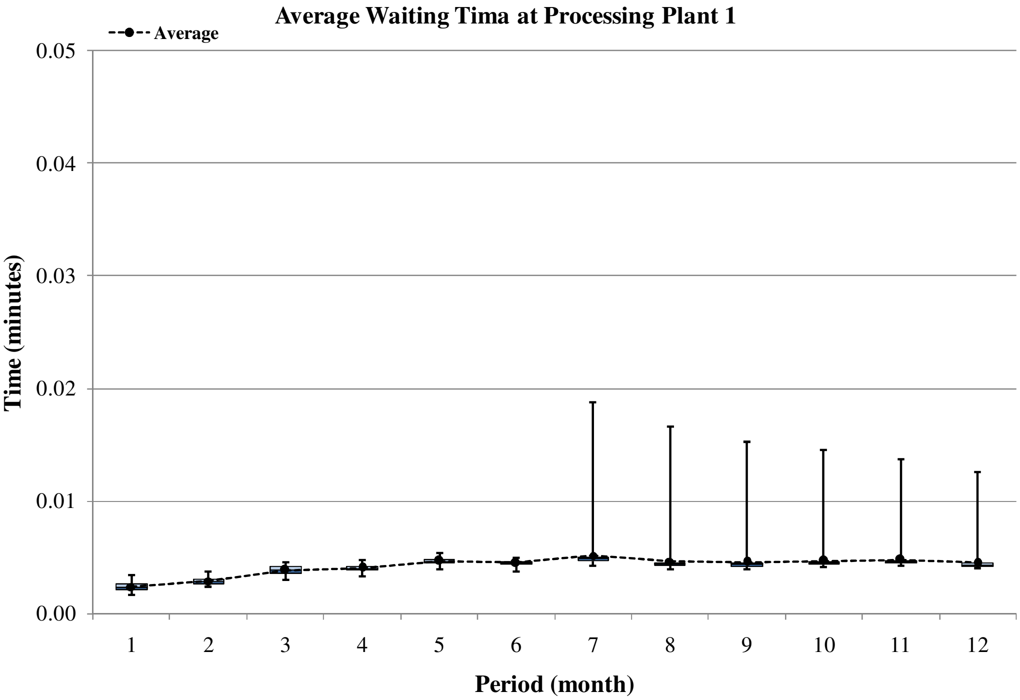

Figure 35.Box plot of average truck waiting time at processing plant 1 in new scenario

Table 30. Statistics of average truck waiting time at processing plant 1 in new scenario

Month	Minimum (min)	1st Quartile (min)	Median (min)	3rd Quartile (min)	Maximum (min)	Average (min)	Reduction (%)
1	0.002	0.002	0.002	0.003	0.003	0.002	99.86
2	0.002	0.003	0.003	0.003	0.004	0.003	99.86
3	0.003	0.004	0.004	0.004	0.005	0.004	99.81
4	0.003	0.004	0.004	0.004	0.005	0.004	99.81
5	0.004	0.004	0.005	0.005	0.005	0.005	99.77
6	0.004	0.004	0.004	0.005	0.005	0.004	99.80
7	0.004	0.005	0.005	0.005	0.019	0.005	99.77
8	0.004	0.004	0.004	0.005	0.017	0.005	99.81
9	0.004	0.004	0.004	0.005	0.015	0.005	99.82
10	0.004	0.004	0.004	0.005	0.015	0.005	99.82
11	0.004	0.004	0.005	0.005	0.014	0.005	99.81
12	0.004	0.004	0.004	0.004	0.013	0.005	99.82

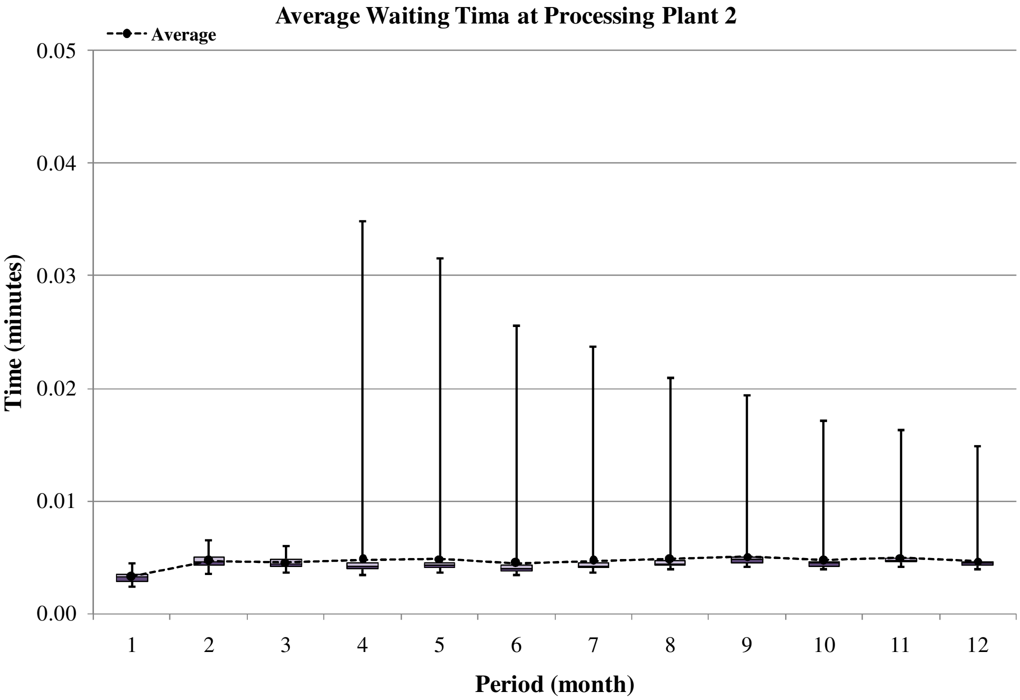

Figure 36. Box plot of average truck waiting time at processing plant 2 in new scenario

Table 31. Statistics of average truck waiting time at processing plant 2 in new scenario

Month	Minimum (min)	1st Quartile (min)	Median (min)	3rd Quartile (min)	Maximum (min)	Average (min)	Reduction (%)
1	0.002	0.003	0.003	0.004	0.004	0.003	99.77
2	0.003	0.004	0.005	0.005	0.007	0.005	99.75
3	0.004	0.004	0.004	0.005	0.006	0.005	99.78
4	0.003	0.004	0.004	0.004	0.035	0.005	99.78
5	0.004	0.004	0.004	0.005	0.032	0.005	99.78
6	0.003	0.004	0.004	0.004	0.026	0.004	99.81
7	0.004	0.004	0.004	0.004	0.024	0.005	99.81
8	0.004	0.004	0.004	0.005	0.021	0.005	99.81
9	0.004	0.004	0.005	0.005	0.019	0.005	99.80
10	0.004	0.004	0.004	0.005	0.017	0.005	99.83
11	0.004	0.005	0.005	0.005	0.016	0.005	99.82
12	0.004	0.004	0.004	0.005	0.015	0.005	99.84

Any improvement in truck waiting time would impact the truck queue length and truck cycle time and, thus, improve the system's total efficiency. Because the average queue length is directly related to the average waiting time, in the new scenario the queue lengths at processing plants 1 and 2 decrease significantly.

Regarding truck cycle times, as explained before, one of the factors that affects truck cycle time is the velocity of trucks and shovels. Velocity is a factor that cannot be altered because it is related to such considerations as the types of trucks and shovels being used, the road and weather conditions, and the driver's experience.

Another component in truck cycle time is the waiting time. In the new scenario, because the truck waiting time is decreased, the expectation is that there will be lower truck cycle times. Average cycle times during day and night shifts are separately illustrated in Figure 37 and Figure 38. Corresponding statistics are presented in Table 32 and Table 33, respectively. Also the "big picture" of the resulting cycle times is shown in Figure 39to make it easier to compare the average cycle times between day and night shifts. Corresponding statistics are presented in Table 34.

In the new scenario, some material that was supposed to go the processing plants is delivered to stockpiles because of a crusher failure. Because a crusher failure is a stochastic variable, the material delivered to the processing plants and stockpiles varies in different replications.

In this scenario, in addition to scheduled reclamation from stockpiles, extra reclamation should be done to meet the production target. The unplanned flow of material from each period is reclaimed during the subsequent period. Therefore, there are variations in reclaimed material tonnage as well.

To see these variations, monthly delivered material tonnage to each destination is studied in detail. The average material tonnage delivered directly from the mine to processing plants 1 and 2 is illustrated in Figure 40 and Figure41, and the corresponding statistics are presented in Table 35 and Table 36, respectively. The monthly reclaimed material tonnage from stockpile 1 that is delivered to processing plant 1 is summarized in Figure 42 and Table 37. In the same manner, the monthly reclaimed material tonnage from stockpile 2 that is delivered to processing plant 2 is summarized in Figure 43 and Table 38.

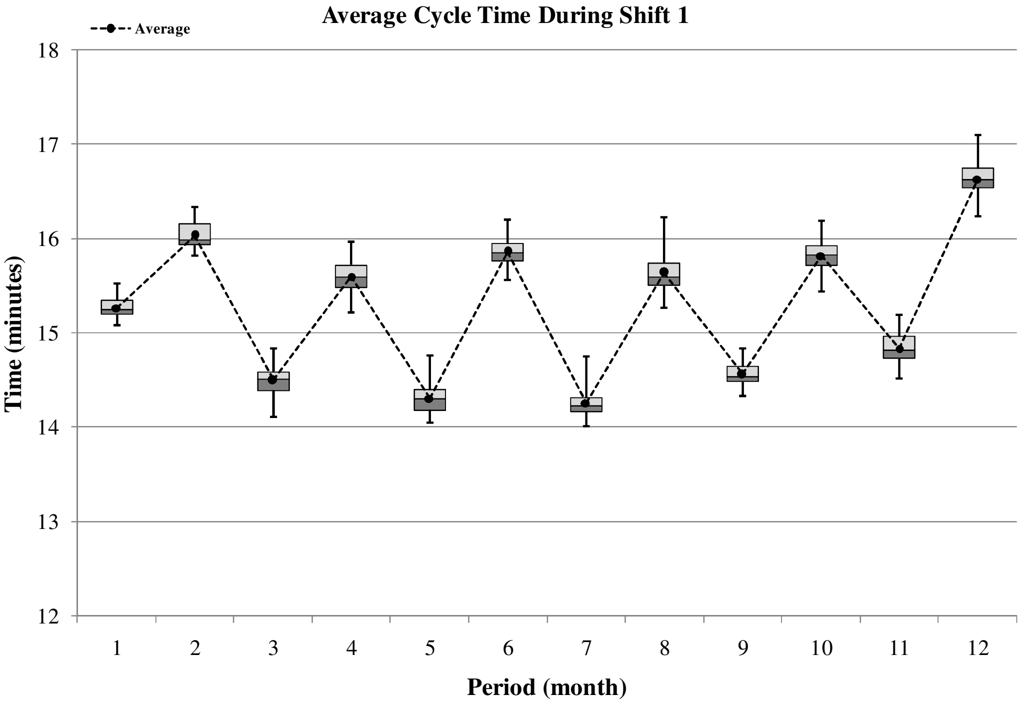

Figure 37. Box plot of average cycle time during day shift in new scenario

Table 32. Statistics of average cycle time during day shift in new scenario

Month	Minimum (min)	1st Quartile (min)	Median (min)	3rd Quartile (min)	Maximum (min)	Average (min)	Improvement (%)
1	15.08	15.20	15.25	15.35	15.53	15.27	3.14
2	15.82	15.93	15.99	16.16	16.33	16.03	2.96
3	14.11	14.39	14.51	14.59	14.84	14.50	2.17
4	15.22	15.48	15.59	15.72	15.97	15.60	3.50
5	14.05	14.19	14.30	14.40	14.76	14.31	2.54
6	15.56	15.77	15.85	15.95	16.20	15.86	6.48
7	14.01	14.17	14.23	14.31	14.76	14.26	4.43
8	15.27	15.51	15.60	15.75	16.23	15.64	7.01
9	14.34	14.48	14.54	14.65	14.84	14.56	5.19
10	15.44	15.72	15.83	15.93	16.19	15.82	5.25
11	14.52	14.73	14.82	14.97	15.20	14.84	4.37
12	16.24	16.55	16.63	16.75	17.10	16.63	6.18

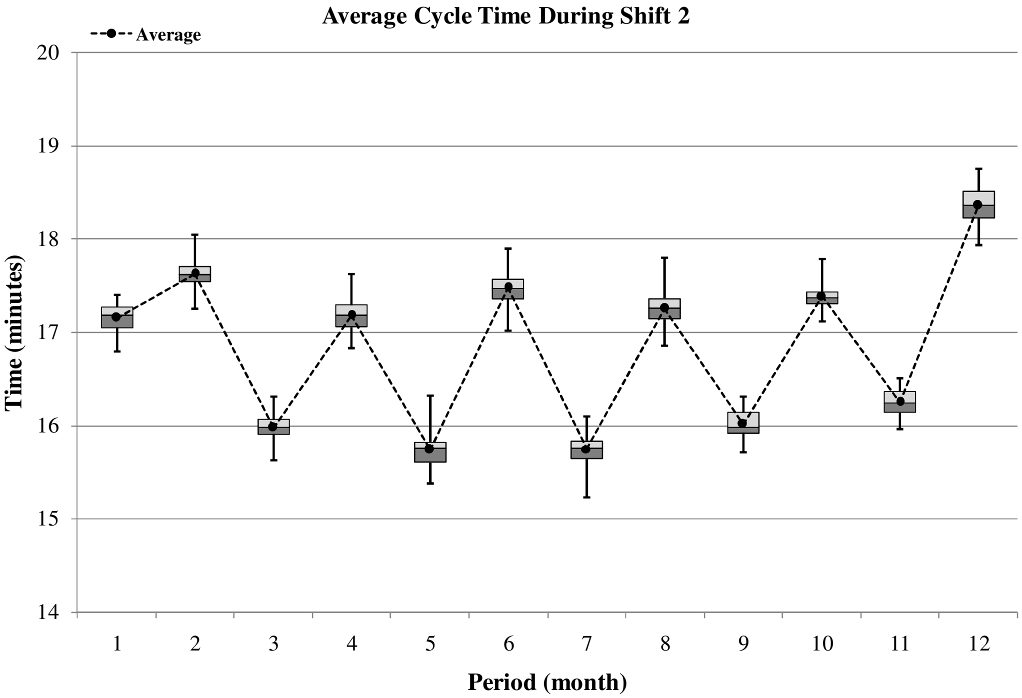

Figure 38. Box plot of average cycle time during night shift in new scenario

Table 33. Statistics of average cycle time during night shift in new scenario

Month	Minimum (min)	1st Quartile (min)	Median (min)	3rd Quartile (min)	Maximum (min)	Average (min)	Improvement (%)
1	16.79	17.05	17.18	17.26	17.40	17.15	2.70
2	17.25	17.54	17.62	17.70	18.04	17.63	5.95
3	15.63	15.91	15.98	16.07	16.31	15.98	3.30
4	16.83	17.06	17.18	17.29	17.62	17.18	5.46
5	15.37	15.60	15.75	15.82	16.32	15.74	2.23
6	17.01	17.36	17.47	17.57	17.90	17.48	4.76
7	15.23	15.64	15.76	15.83	16.10	15.75	3.19
8	16.85	17.14	17.25	17.36	17.79	17.26	5.80
9	15.71	15.92	15.98	16.14	16.31	16.01	3.74
10	17.12	17.31	17.37	17.44	17.79	17.38	6.95
11	15.96	16.14	16.25	16.36	16.50	16.25	5.30
12	17.93	18.22	18.36	18.51	18.76	18.36	4.95

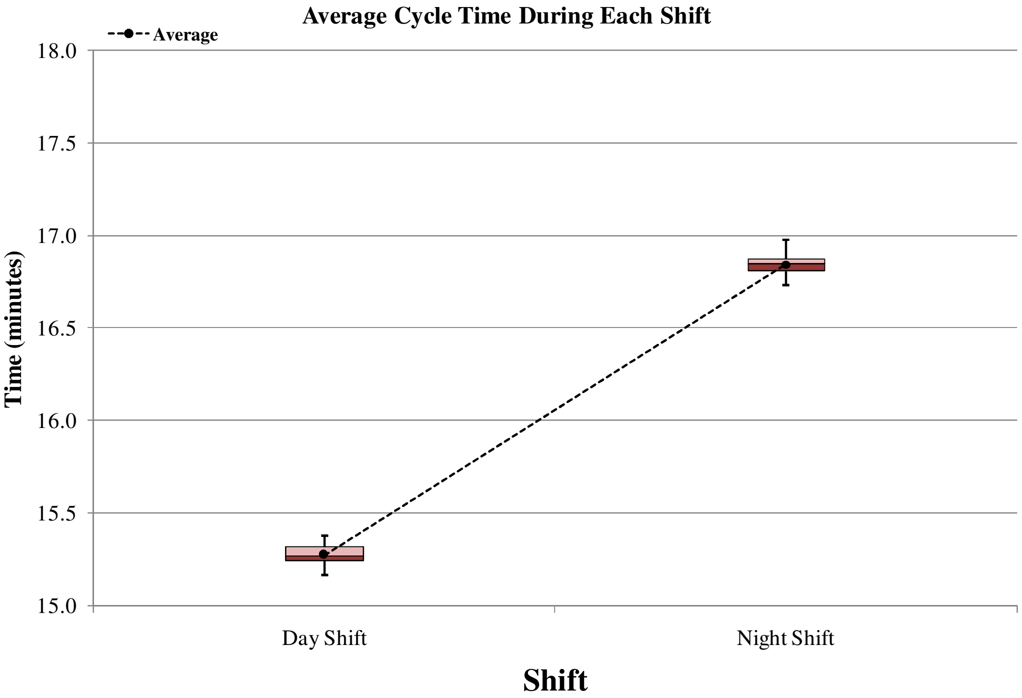

Figure 39. Box plot of average cycle time during each shift in new scenario

Table 34. Statistics of average cycle time during each shift in new scenario

Shift	Minimum (min)	1^{st} Quartile (min)	Median (min)	3^{rd} Quartile (min)	Maximum (min)	Average (min)	Improvement (%)
Day	15.17	15.25	15.27	15.32	15.38	15.28	4.50
Night	16.74	16.81	16.85	16.88	16.98	16.85	4.59

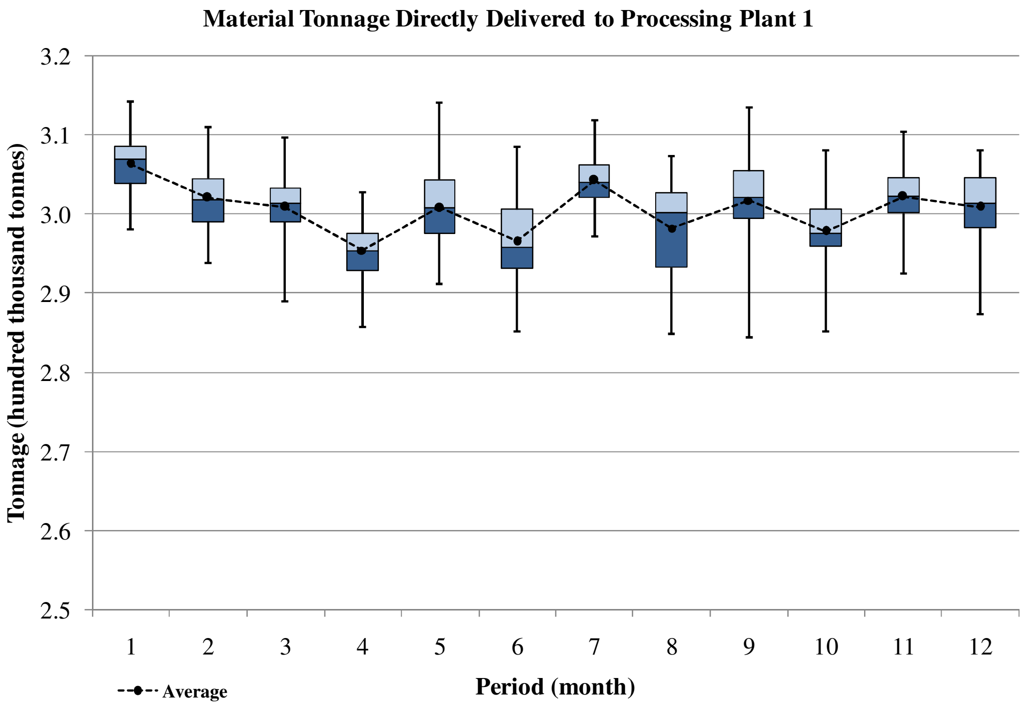

Figure 40. Box plot of material tonnage directly delivered to processing plant 1 in the new scenario

Table 35. Statistics of material tonnage directly delivered to processing plant 1 in the new scenario (hundred thousand tonnes)

Month	Minimum	1st Quartile	Median	3rd Quartile	Maximum	Average
1	2.98	3.04	3.07	3.09	3.14	3.06
2	2.94	2.99	3.02	3.04	3.11	3.02
3	2.89	2.99	3.01	3.03	3.10	3.01
4	2.86	2.93	2.95	2.98	3.03	2.95
5	2.91	2.98	3.01	3.04	3.14	3.01
6	2.85	2.93	2.96	3.01	3.08	2.97
7	2.97	3.02	3.04	3.06	3.12	3.04
8	2.85	2.93	3.00	3.03	3.07	2.98
9	2.84	2.99	3.02	3.05	3.13	3.02
10	2.85	2.96	2.98	3.01	3.08	2.98
11	2.92	3.00	3.02	3.05	3.10	3.02
12	2.87	2.98	3.01	3.05	3.08	3.01

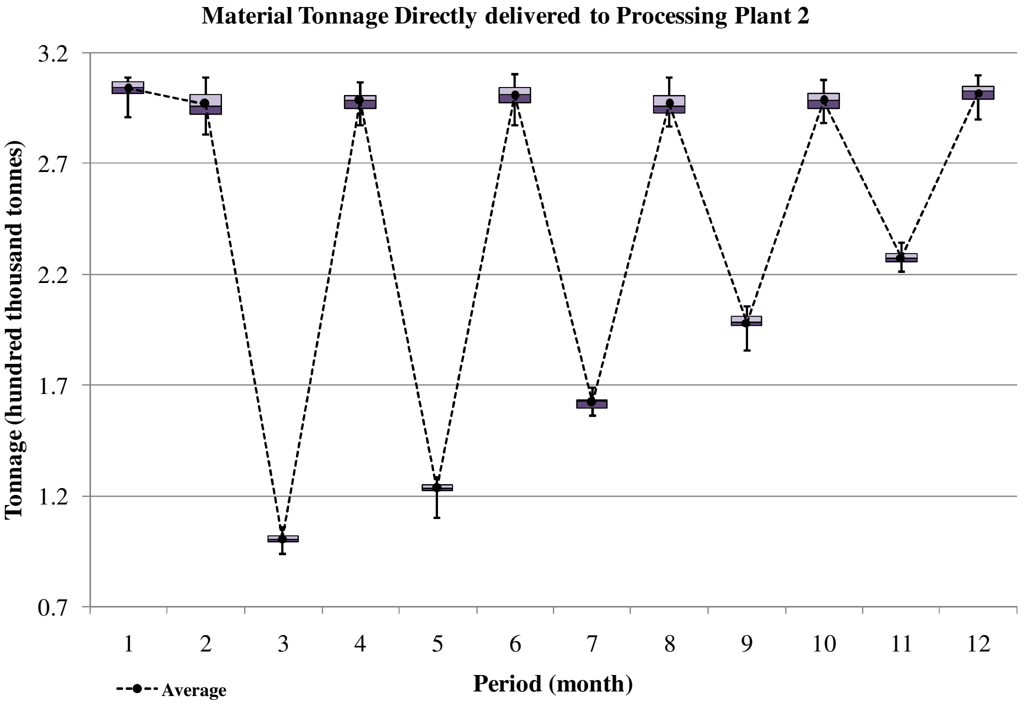

Figure41. Box plot of material tonnage directly delivered to processing plant 2 in the new scenario

Table 36. Statistics of material tonnage directly delivered to processing plant 2 in the new scenario (hundred thousand tonnes)

Month	Minimum	1st Quartile	Median	3rd Quartile	Maximum	Average
1	2.91	3.02	3.05	3.07	3.09	3.04
2	2.83	2.92	2.96	3.01	3.09	2.97
3	0.94	1.00	1.01	1.02	1.06	1.01
4	2.87	2.95	2.99	3.01	3.07	2.98
5	1.10	1.23	1.24	1.25	1.29	1.23
6	2.87	2.98	3.01	3.04	3.10	3.01
7	1.56	1.60	1.63	1.64	1.69	1.62
8	2.87	2.93	2.96	3.01	3.09	2.97
9	1.86	1.97	1.98	2.01	2.05	1.98
10	2.89	2.95	2.98	3.02	3.07	2.98
11	2.21	2.26	2.27	2.30	2.34	2.27
12	2.90	2.99	3.03	3.05	3.10	3.02

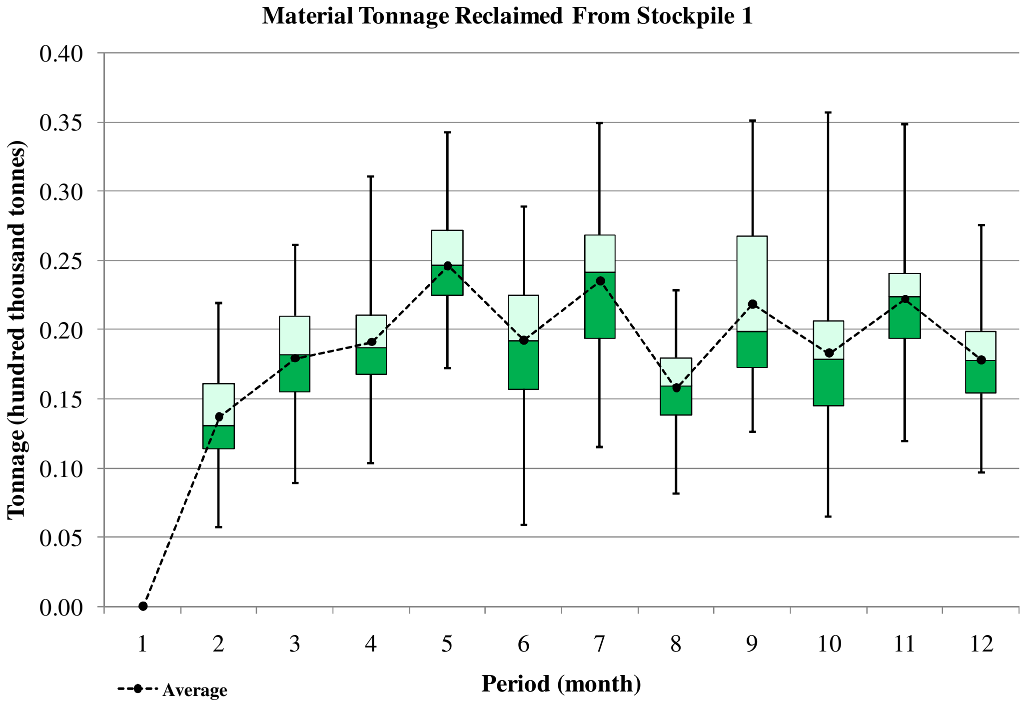

Figure 42. Box plot of material tonnage reclaimed from stockpile 1 and delivered to processing plant 1 in the new scenario

Table 37. Statistics of material tonnage reclaimed from stockpile 1 and delivered to processing plant 1 in the new scenario (hundred thousand tonnes)

Month	Minimum	1st Quartile	Median	3rd Quartile	Maximum	Average
1	0.00	0.00	0.00	0.00	0.00	0.00
2	0.06	0.11	0.13	0.16	0.22	0.14
3	0.09	0.16	0.18	0.21	0.26	0.18
4	0.10	0.17	0.19	0.21	0.31	0.19
5	0.17	0.22	0.25	0.27	0.34	0.25
6	0.06	0.16	0.19	0.22	0.29	0.19
7	0.12	0.19	0.24	0.27	0.35	0.23
8	0.08	0.14	0.16	0.18	0.23	0.16
9	0.13	0.17	0.20	0.27	0.35	0.22
10	0.07	0.15	0.18	0.21	0.36	0.18
11	0.12	0.19	0.22	0.24	0.35	0.22
12	0.10	0.15	0.18	0.20	0.28	0.18

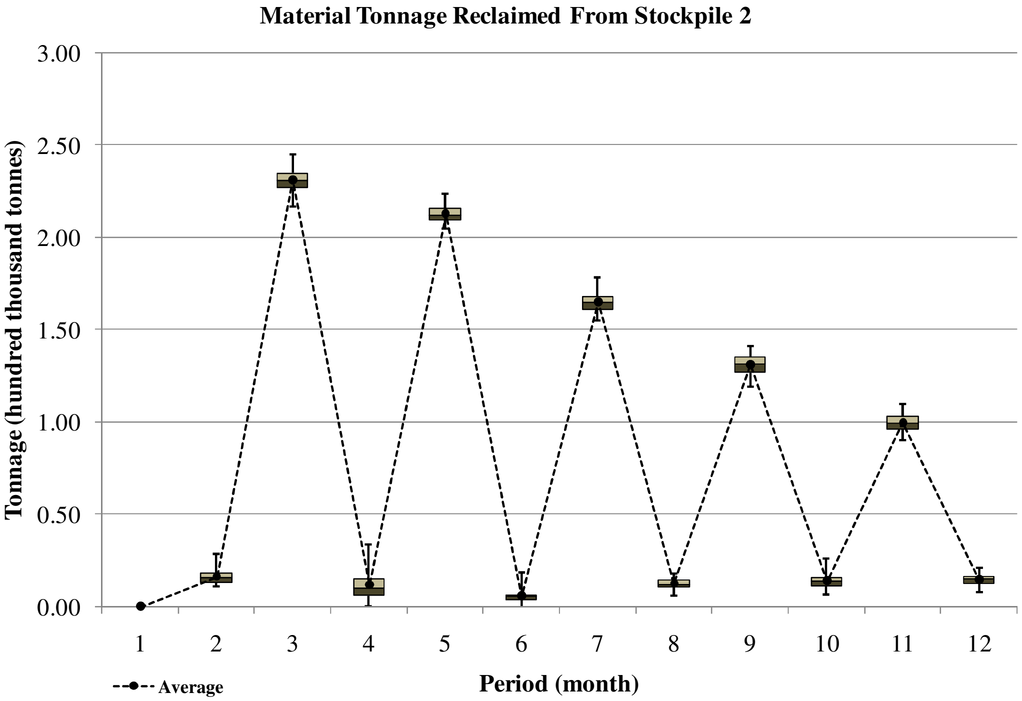

Figure 43. Box plot of material tonnage reclaimed from stockpile 1 and delivered to processing plant 1 in the new scenario

Table 38. Statistics of material tonnage reclaimed from stockpile 1 and delivered to processing plant 1 in the new scenario (hundred thousand tonnes)

Month	Minimum	1st Quartile	Median	3rd Quartile	Maximum	Average
1	0.00	0.00	0.00	0.00	0.00	0.00
2	0.11	0.13	0.15	0.18	0.29	0.16
3	2.16	2.27	2.31	2.35	2.45	2.31
4	0.00	0.06	0.10	0.15	0.34	0.12
5	2.05	2.09	2.12	2.16	2.24	2.13
6	0.00	0.04	0.05	0.07	0.19	0.06
7	1.55	1.61	1.65	1.68	1.78	1.65
8	0.06	0.11	0.12	0.15	0.18	0.12
9	1.19	1.27	1.32	1.35	1.41	1.31
10	0.07	0.11	0.14	0.16	0.26	0.14
11	0.91	0.96	1.00	1.03	1.09	1.00
12	0.08	0.13	0.15	0.16	0.21	0.15

Regarding stockpiles, the monthly delivered total tonnage of material to stockpiles 1 and 2 are shown in Figure 44 and Figure 45, and the corresponding statistics are displayed in Table 39 and Table 40, respectively. In the new scenario, the content of stockpile at each period is sourced from two different flows of material. One is a planned flow of material which is based on the short-term production schedule. The other is the material flow which was supposed to go to the processing plant, but is delivered to the stockpile because of crusher failure. The box plots of this flow of material to stockpiles 1 and 2 are pictures in Figure 46 and Figure 47, respectively (also see Table 41 and Table 42).

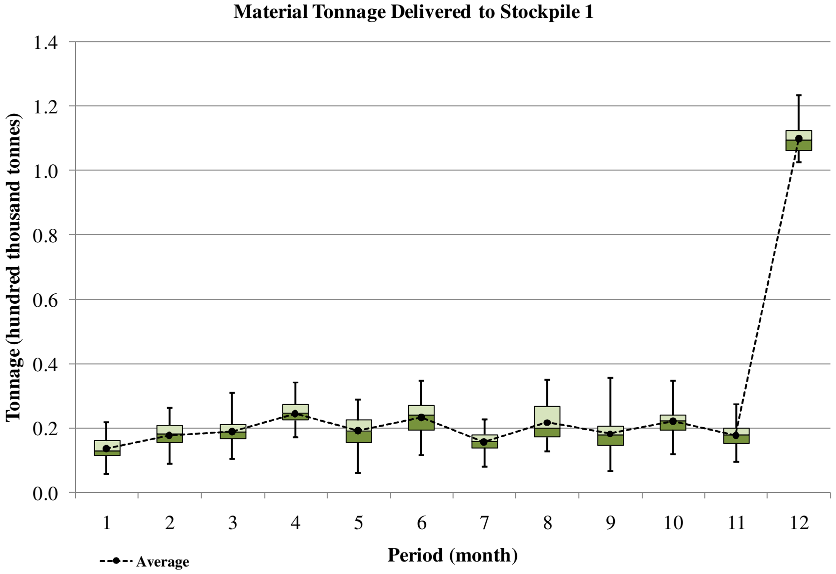

Figure 44. Box plot of total material tonnage delivered to stockpile 1 in the new scenario

Table 39. Statistics of total material tonnage delivered to stockpile 1 in the new scenario (hundred thousand tonnes)

Month	Minimum	1st Quartile	Median	3rd Quartile	Maximum	Average
1	0.06	0.11	0.13	0.16	0.22	0.14
2	0.09	0.16	0.18	0.21	0.26	0.18
3	0.10	0.17	0.19	0.21	0.31	0.19
4	0.17	0.22	0.25	0.27	0.34	0.25
5	0.06	0.16	0.19	0.22	0.29	0.19
6	0.12	0.19	0.24	0.27	0.35	0.23
7	0.08	0.14	0.16	0.18	0.23	0.16
8	0.13	0.17	0.20	0.27	0.35	0.22
9	0.07	0.15	0.18	0.21	0.36	0.18
10	0.12	0.19	0.22	0.24	0.35	0.22
11	0.10	0.15	0.18	0.20	0.28	0.18
12	1.03	1.06	1.09	1.12	1.23	1.10

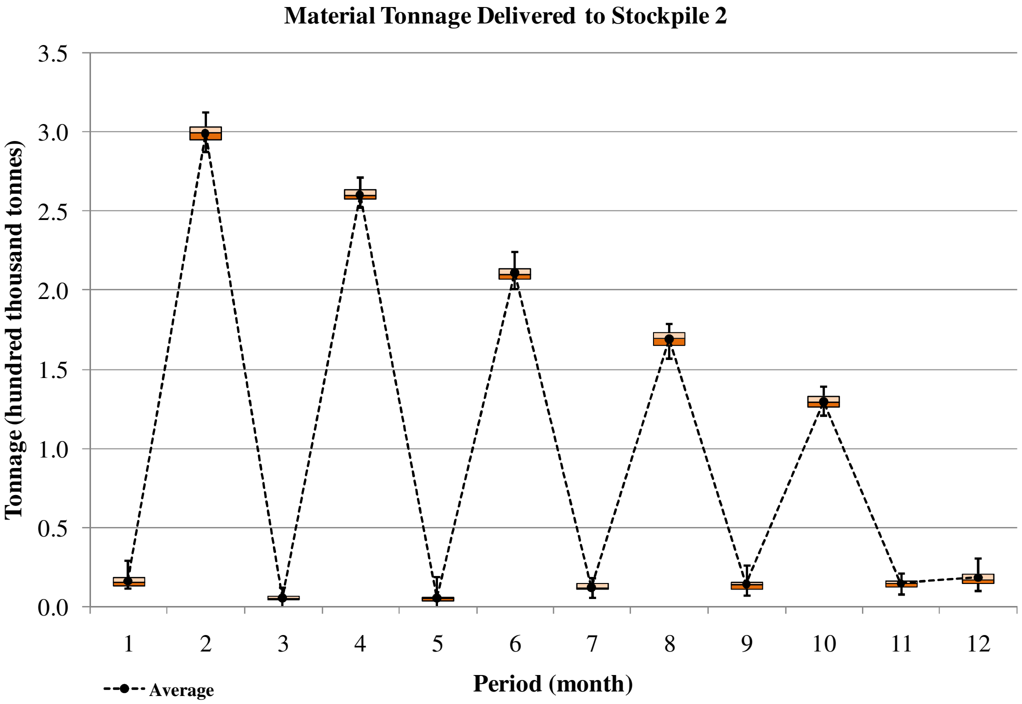

Figure 45. Box plot of total material tonnage delivered to stockpile 2 in the new scenario

Table 40. Statistics of total material tonnage delivered to stockpile 2 in the new scenario (hundred thousand tonnes)

Month	Minimum	1st Quartile	Median	3rd Quartile	Maximum	Average
1	0.11	0.13	0.15	0.18	0.29	0.16
2	2.87	2.95	3.00	3.03	3.12	2.99
3	0.00	0.04	0.05	0.07	0.12	0.06
4	2.52	2.57	2.60	2.63	2.71	2.60
5	0.00	0.04	0.05	0.06	0.19	0.05
6	2.01	2.07	2.10	2.14	2.24	2.11
7	0.06	0.11	0.12	0.15	0.18	0.12
8	1.57	1.65	1.69	1.73	1.79	1.69
9	0.07	0.11	0.14	0.16	0.26	0.14
10	1.20	1.26	1.29	1.33	1.39	1.29
11	0.08	0.13	0.15	0.16	0.21	0.15
12	0.10	0.15	0.17	0.21	0.30	0.18

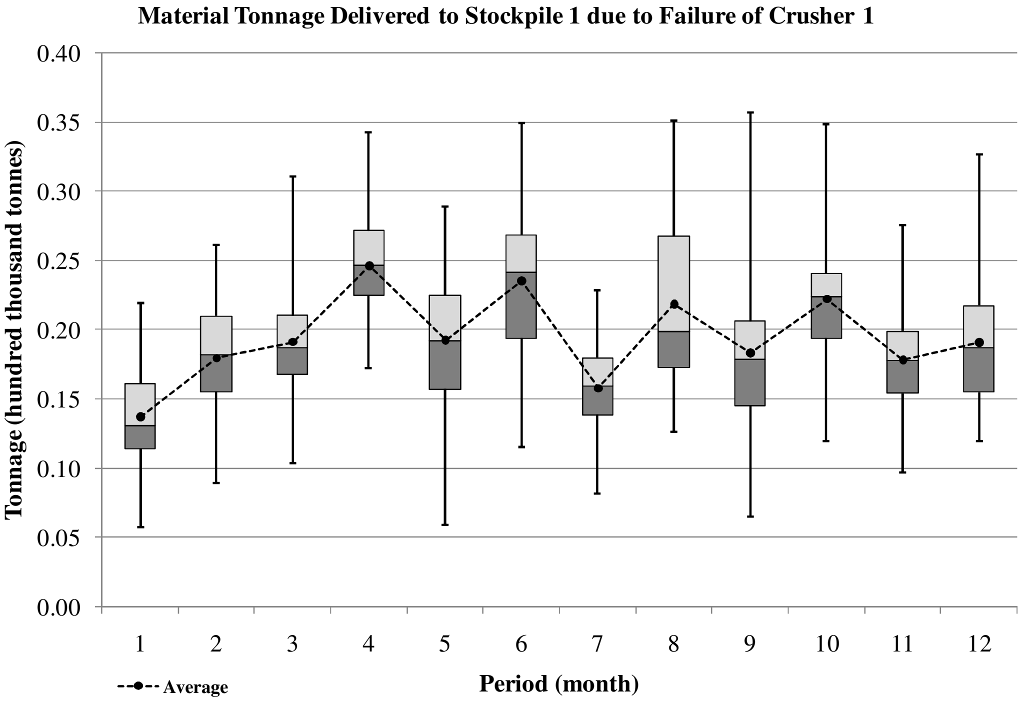

Figure 46. Box plot of material tonnage delivered to stockpile 1 due to failure of crusher 1

Table 41. Statistics of material tonnage delivered to stockpile 1 due to failure of crusher 1 (hundred thousand tonnes)

Month	Minimum	1st Quartile	Median	3rd Quartile	Maximum	Average
1	0.06	0.11	0.13	0.16	0.22	0.14
2	0.09	0.16	0.18	0.21	0.26	0.18
3	0.10	0.17	0.19	0.21	0.31	0.19
4	0.17	0.22	0.25	0.27	0.34	0.25
5	0.06	0.16	0.19	0.22	0.29	0.19
6	0.12	0.19	0.24	0.27	0.35	0.23
7	0.08	0.14	0.16	0.18	0.23	0.16
8	0.13	0.17	0.20	0.27	0.35	0.22
9	0.07	0.15	0.18	0.21	0.36	0.18
10	0.12	0.19	0.22	0.24	0.35	0.22
11	0.10	0.15	0.18	0.20	0.28	0.18
12	0.12	0.15	0.19	0.22	0.33	0.19

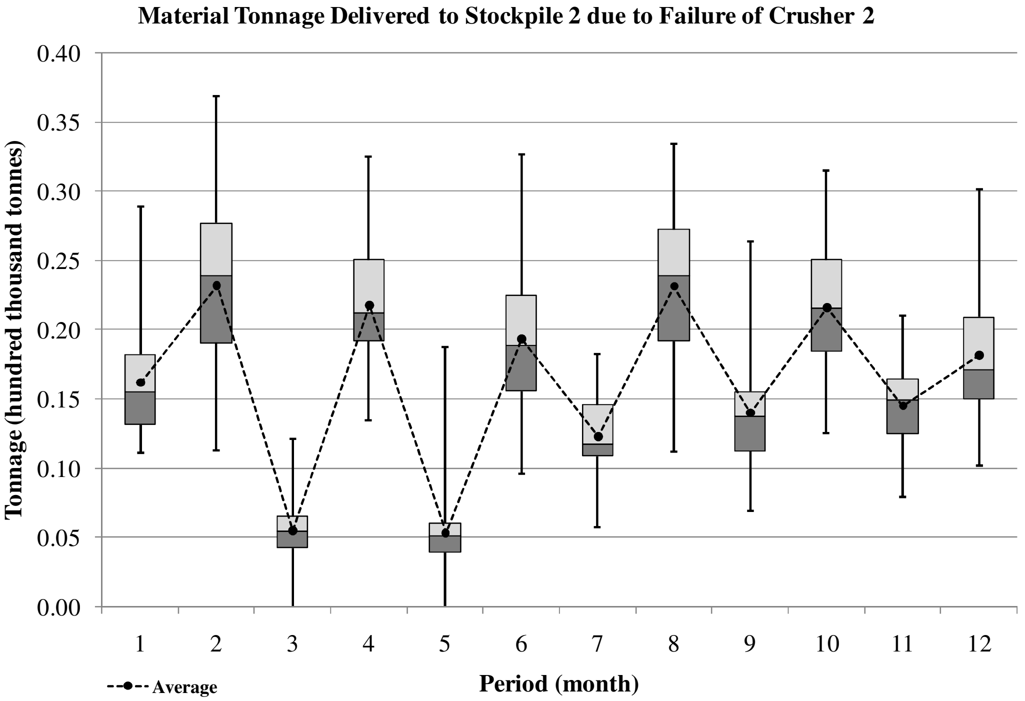

Figure 47. Box plot of material tonnage delivered to stockpile 1 due to failure of crusher 2

Table 42. Statistics of material tonnage delivered to stockpile 1 due to failure of crusher 2 (hundred thousand tonnes)

Month	Minimum	1st Quartile	Median	3rd Quartile	Maximum	Average
1	0.11	0.13	0.15	0.18	0.29	0.16
2	0.11	0.19	0.24	0.28	0.37	0.23
3	0.00	0.04	0.05	0.07	0.12	0.06
4	0.13	0.19	0.21	0.25	0.33	0.22
5	0.00	0.04	0.05	0.06	0.19	0.05
6	0.10	0.16	0.19	0.22	0.33	0.19
7	0.06	0.11	0.12	0.15	0.18	0.12
8	0.11	0.19	0.24	0.27	0.33	0.23
9	0.07	0.11	0.14	0.16	0.26	0.14
10	0.13	0.18	0.22	0.25	0.31	0.22
11	0.08	0.13	0.15	0.16	0.21	0.15
12	0.10	0.15	0.17	0.21	0.30	0.18

Figure 48 summarizes the data related to the material tonnage delivered to each destination in the new scenario. Average values are used to generate this figure and are presented in Table 43. The total ore tonnage delivered to processing plant, both directly delivered and reclaimed, deviates from the optimal target. Figure 49 pictures these deviations in terms of percentages of the optimal ore production target. Table 44 summarizes the statistics of ore tonnage deviations in percentages. Table 45 shows the deviations in terms of tonnage.

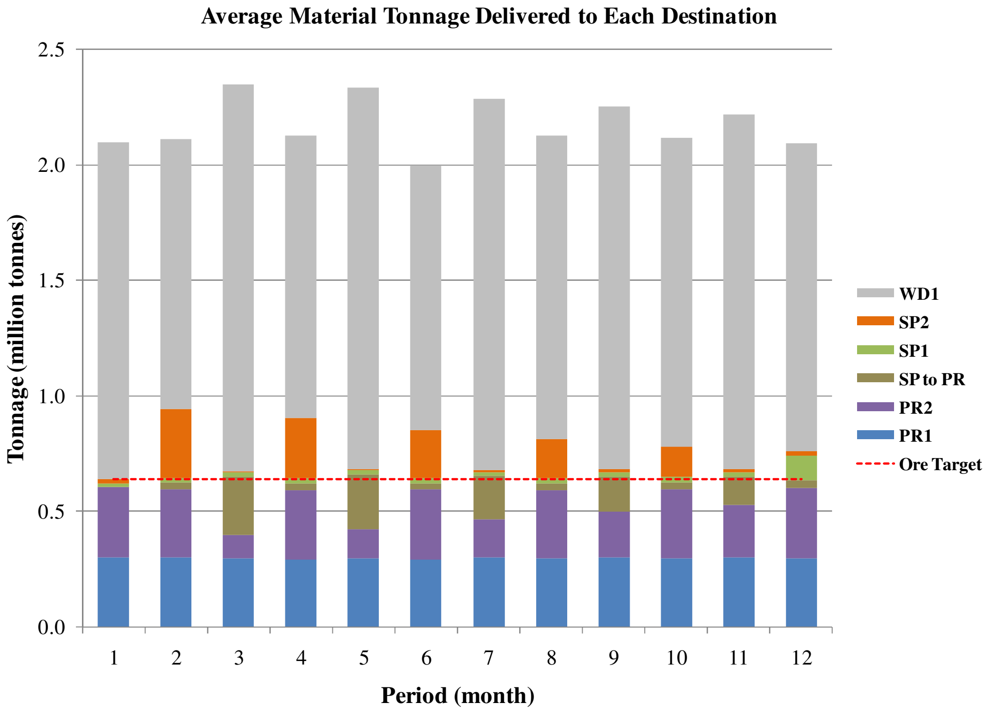

Figure 48. Average material tonnage delivered to each destination in the new scenario

Table 43. Statistics of average material tonnage delivered to each destination in the new scenario (million tonnes)

Month	PR1	PR2	SP1 to PR1	SP1	SP2	WD1
1	0.31	0.30	0.00	0.01	0.02	1.46
2	0.30	0.30	0.03	0.02	0.30	1.17
3	0.30	0.10	0.25	0.02	0.01	1.67
4	0.30	0.30	0.03	0.02	0.26	1.22
5	0.30	0.12	0.24	0.02	0.01	1.65
6	0.30	0.30	0.03	0.02	0.21	1.14
7	0.30	0.16	0.19	0.02	0.01	1.61
8	0.30	0.30	0.03	0.02	0.17	1.31
9	0.30	0.20	0.15	0.02	0.01	1.57
10	0.30	0.30	0.03	0.02	0.13	1.34
11	0.30	0.23	0.12	0.02	0.01	1.54
12	0.30	0.30	0.03	0.11	0.02	1.33

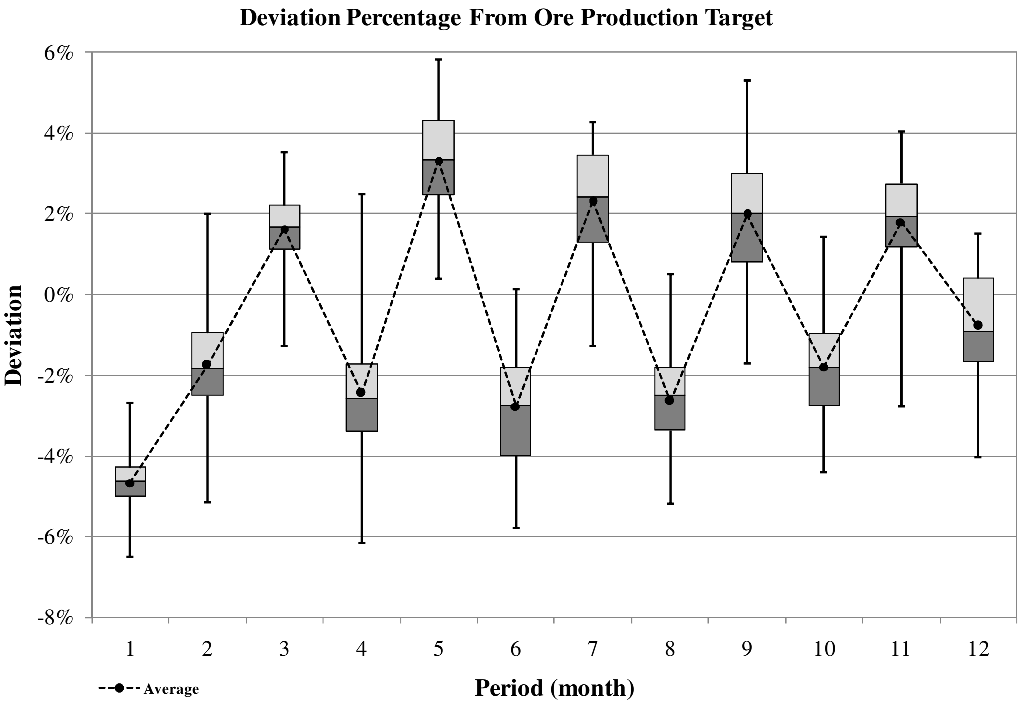

Figure 49. Box plot of the percentage of average delivered ore that has deviated from the ore production target

Table 44. Statistics of the percentage of average delivered ore that has deviated from the ore production target

Month	Minimum (%)	1st Quartile (%)	Median (%)	3rd Quartile (%)	Maximum (%)	Average (%)
1	-6.51	-5.01	-4.61	-4.28	-2.67	-4.67
2	-5.14	-2.49	-1.84	-0.95	2.01	-1.76
3	-1.27	1.12	1.68	2.21	3.54	1.63
4	-6.15	-3.39	-2.59	-1.73	2.50	-2.44
5	0.40	2.49	3.33	4.31	5.83	3.32
6	-5.77	-3.97	-2.76	-1.79	0.15	-2.77
7	-1.26	1.30	2.43	3.46	4.28	2.31
8	-5.19	-3.36	-2.50	-1.80	0.52	-2.64
9	-1.69	0.82	2.01	2.98	5.32	1.98
10	-4.42	-2.76	-1.81	-0.98	1.43	-1.80
11	-2.76	1.20	1.93	2.75	4.03	1.80
12	-4.03	-1.65	-0.91	0.40	1.51	-0.77

Table 45. Statistics of the tonnage of average delivered ore that has deviated from the ore production target (thousand tonnes)

Month	Minimum	1st Quartile	Median	3rd Quartile	Maximum	Average
1	-41.65	9.61	2.52	2.10	10.34	-29.89
2	-32.93	16.96	4.19	5.71	18.91	-11.26
3	-8.11	15.29	3.60	3.38	8.49	10.41
4	-39.34	17.65	5.11	5.52	27.03	-15.62
5	2.56	13.38	5.37	6.26	9.75	21.27
6	-36.94	11.50	7.79	6.19	12.42	-17.74
7	-8.06	16.35	7.27	6.60	5.21	14.78
8	-33.20	11.70	5.49	4.46	14.88	-16.92
9	-10.82	16.07	7.61	6.24	14.95	12.66
10	-28.28	10.62	6.06	5.32	15.44	-11.51
11	-17.64	25.30	4.68	5.24	8.22	11.49
12	-25.81	15.24	4.76	8.36	7.11	-4.95

4.5 Verification of the Simulation Model

The usefulness of the model is tied to its accuracy. In this section, the accuracy of the basic simulation model is verified in different ways. First, some criteria are established to compare the simulation model results to the short-term plan and mine specifications results. The following criteria are used to evaluate the accuracy of the basic model:

- Total delivered ore and waste tonnage:

  As presented in Figure 17 and Table 11, simulation results show that the total amount of ore delivered to the processing plants is 640,000 tonnes. This includes both the material directly delivered to processing plants and the material reclaimed from the stockpiles. The total amount of ore delivered to each of the processing plants is 320,000 tonnes. In addition, results show that the total amount of material extracted from the mine is 2,200,000 tonnes.

  Based on the optimal short-term schedule, the mining capacity is 2,200,000 tonnes, and each processing plant uses 320,000 tonnes of its capacity. Therefore, the results from the simulation model are consistent with the optimal short-term production schedule. These results confirm that the model is accurate and the material is neither created nor lost in the model. Although there model contains stochastic variables, these results are stable for all 50 replications.

- Weighted average grade of delivered material:

  The grades of elements that include magnetic iron, phosphor, and sulfur are obtained for each month. Simulation results show that the average grade of material delivered to each destination is within the range defined by mine specifications for that destination (see

  Table 46). These results prove the accuracy of the model. Since the material tonnage delivered to the destinations is stable for all replications, the average grades are also stable.

Table 46. Resulting average grade ranges compared to mine-grade specifications

Destination	Element	Resulting Range (%)	Mine Range (%)
Processing Plant 1	MWT	73.70 – 78.00	73 – 78
	Phosphor	0.14 – 0.16	0 – 0.3
	Sulfur	1.50 – 1.96	0 – 2
Processing Plant 2	MWT	78.00 – 82.00	78 – 82
	Phosphor	0.11 – 0.15	0 – 0.3
	Sulfur	1.47 – 1.79	0 – 2
Stockpile 1	MWT	74.00	71 – 74
	Phosphor	0.16	0 – 0.3
	Sulfur	1.79	0 – 3
Stockpile 2	MWT	75.72 – 75.80	75 – 77
	Phosphor	0.12 – 0.14	0 – 0.3
	Sulfur	1.20 – 1.28	0 – 2

Moreover, another method, called deterministic simulation, is used to verify the proposed stochastic simulation model. In this method, all failures are ignored and all random variables are replaced with their mean values. Table 47 presents the random variables and their mean values.

Table 47. Random variables and their mean values

Stochastic Variable	Mean
Loaded Truck Velocity (km/h)	18
Empty Truck Velocity (km/h)	30
Shovel Velocity (km/h)	6
Load Time (s)	15
Dump Time (s)	12.6
Load-pass Tonnage (tonnes)	35

Some sample entities (portions of mining-cuts) are chosen to study the behavior of trucks that are operating with those entities. Truck cycle time is the most important indicator of a truck’s behavior. Truck cycle time consists of the time that it takes the truck to complete the following tasks:

- Travel from pit-exit point to the mining-cut’s location
- Be fully loaded
- Travel to the predetermined destination
- Dump the load
- Travel from the destination back to the pit-exit point

The developed deterministic model is modified in order to capture the starting time, finishing time, and duration of each of these tasks for trucks working with a sample mining-cut. Then, the time that it takes a truck to complete each task is calculated by hand. Finally, the results from the deterministic model are compared to the manual calculations.

An example of a mining-cut for which this procedure is applied is the one with the ID number of 60 and a total tonnage of 22,568.29 tonnes. Based on the short-term schedule, 5% of this mining-cut (1,128.41 tonnes) should be extracted at period 1 and be delivered to processing plant 1.

The simulation results show that this portion of the mining-cut has been completely extracted in 11 truck visits. Each truck has delivered a load of 105 tonnes, except for the last truck, which has delivered 78.41 tonnes. The following manual calculation shows that trucks have delivered material tonnage exactly equal to the entity's tonnage.

$$\begin{aligned} \textit{Total delivered tonnage} &= 10 \ \textit{(truck visitis)} \times 105 \ \textit{(tonnes per truck)} \\ &+ 1 \ \textit{(truck visits)} \times 78.41 \ \textit{(tonnes per truck)} \\ &= 1{,}128.41 \ \textit{(tonnes)} \end{aligned}$$

The results and manual calculations for each of the aforementioned truck cycle components are explained in detail as follows:

Truck travels from the pit-exit point to the mining-cut's location:

This sample mining-cut is located 2,014.49 meters away from the pit-exit point. The time that takes an empty truck to travel from pit-exit point to the mining-cut's location is manually calculated as follows. The resulting data regarding all truck visits to the mining-cut is summarized in Table 48. The last column of the table proves the consistency of the simulation results with manual calculations.

$$\begin{aligned} &\textit{Travel time from pit-exit point to mining-cut's location} \\ &= \frac{\textit{distance between pit-exit point and mining-cut}}{\textit{empty truck's velocity}} \\ &= \frac{2{,}014.49 \ \textit{(m)}}{600 \ \textit{(m / min)}} \\ &= 3.36 \ \textit{(min)} \end{aligned}$$

Table 48. Time results for the operation of the truck travelling to a mining-cut

Truck Visit	Start Time (minutes)	Finish Time (minutes)	Duration (minutes)
1	0.00	3.36	3.36
2	4.11	7.46	3.36
3	8.21	11.57	3.36
4	12.32	15.68	3.36
5	16.43	19.79	3.36
6	20.54	23.89	3.36
7	24.64	28.00	3.36
8	28.75	32.11	3.36
9	32.86	36.22	3.36
10	36.97	40.32	3.36
11	41.07	44.43	3.36

Truck is fully loaded:

It takes three load-passes to fully load a truck. Because each load-pass takes 0.25 minutes, it takes 0.75 minutes for a truck to be fully loaded. Table 49summarizes the resulting data regarding the task of fully loading a truck. The last column of the table confirms the consistency of the simulation results with manual calculations. As for the last truck visit, which has delivered 78.41 tonnes, this truck is also loaded after three load-passes (two 35 tonnes and one 8.41 tonnes).

Table 49. Time results for the operation of a truck being fully loaded

Truck Visit	Start Time (minutes)	Finish Time (minutes)	Duration (minutes)
1	3.36	4.11	0.75
2	7.46	8.21	0.75
3	11.57	12.32	0.75
4	15.68	16.43	0.75
5	19.79	20.54	0.75
6	23.89	24.64	0.75
7	28.00	28.75	0.75
8	32.11	32.86	0.75
9	36.22	36.97	0.75
10	40.32	41.07	0.75
11	44.43	45.18	0.75

Truck travels to the predetermined destination:

The short-term schedule has determined that the mining-cut's material should be delivered to processing plant 1. Processing plant 1 is located 1,000 meters from the pit-exit point. The distance between the mining-cut's location and the destination is:

$$\begin{aligned}
&\textit{Distance between mining - cut and destination} \\
&\qquad = \textit{distance between mining - cut and pit - exit point} \\
&\qquad + \textit{distance between pit - exit point and destination} \\
&\qquad = 2{,}014.49\ (m) + 1{,}000\ (m) \\
&\qquad = 3{,}014.49\ (m)
\end{aligned}$$

The time that it takes a loaded truck to travel to the destination is calculated as:

$$\begin{aligned} &\textit{Travel time from mining - cut's location to destination} \\ &\quad = \frac{\textit{distance between mining - cut and destination}}{\textit{loaded truck's velocity}} \\ &\quad = \frac{3{,}014.49\ (m)}{300\ (m/min)} \\ &\quad = 10.05\ (min) \end{aligned}$$

Regarding the task of travelling to the destination, time data is summarized in Table 50. The last column of the table shows that the time it takes a truck to travel to the destination is same as what is calculated by hand.

Table 50. Time results for the operation of a truck travelling to its destination

Truck Visit	Start Time (minutes)	Finish Time (minutes)	Duration (minutes)
1	4.11	14.16	10.05
2	8.21	18.26	10.05
3	12.32	22.37	10.05
4	16.43	26.48	10.05
5	20.54	30.59	10.05
6	24.64	34.69	10.05
7	28.75	38.80	10.05
8	32.86	42.91	10.05
9	36.97	47.02	10.05
10	41.07	51.12	10.05
11	45.18	55.23	10.05

Truck dumps its load at the destination:

The other component of truck cycle time is the time that it takes a truck to dump its load at a destination. The mean value of the dump time was set to 0.21 minutes in the deterministic model. Table 51shows the accuracy of the model, because data resulting from the dumping shows that it takes a typical truck 0.21 minutes to complete the dumping task.

Table 51. Time results for the operation of a truck dumping its load

Truck Visit	Start Time (minutes)	Finish Time (minutes)	Duration (minutes)
1	14.16	14.37	0.21
2	18.26	18.47	0.21
3	22.37	22.58	0.21
4	26.48	26.69	0.21
5	30.59	30.80	0.21
6	34.69	34.90	0.21
7	38.80	39.01	0.21
8	42.91	43.12	0.21
9	47.02	47.23	0.21
10	51.12	51.33	0.21
11	55.23	55.44	0.21

Truck travels from the destination back to the pit-exit point:

Finally, a truck which has dumped its load travels back to the pit-exit point. The time to complete this task is calculated as follows:

$$\begin{aligned}
&\mathit{Travel\ time\ from\ destination\ to\ pit-exit\ point}\\
&\quad= \frac{\mathit{distance\ between\ destination\ and\ pit\text{-}exit\ point}}{\mathit{empty\ truck's\ velocity}}\\
&\quad= \frac{1{,}000\ \ (m)}{600\ \ (m/min)}\\
&\quad= 1.67\ \ (min)
\end{aligned}$$

Table 52 presents the starting time, finish time, and the duration of traveling back to the pit-exit point. Comparing the last column of the table with the calculated value verifies the simulation model. A truck travelling to this mining-cut, but with the ultimate destination of processing plant 1 has a total cycle time of 16.03 minutes.

Table 52. Time results for the operation of a truck travelling back to the pit-exit point

Truck Visit	Start Time (minutes)	Finish Time (minutes)	Duration (minutes)
1	14.37	16.03	1.67
2	18.47	20.14	1.67
3	22.58	24.25	1.67
4	26.69	28.35	1.67
5	30.80	32.46	1.67
6	34.90	36.57	1.67
7	39.01	40.68	1.67
8	43.12	44.78	1.67
9	47.23	48.89	1.67
10	51.33	53.00	1.67
11	55.44	57.11	1.67

4.6 Number of Simulation Replications

Another important issue in stochastic simulation modeling is the number of replications. With the focus on a specific output variable, the simulation model is run for *n* replications. The value resulting from the i^{th} replication for the variable is defined as X_i. Because stochastic simulation uses some random inputs, the output usually differs from one replication to another. Therefore, the results from *n* replications form a random sample (X_1, X_2, . . ., X_n).

It is assumed that the X_is are independent and identically distributed random variables from a normal density function with $\theta = E[X_i]$ and variance $\text{Var}[X_i]=\sigma^2$. From confidence interval theory, it is known that a $100\times(1-\alpha)$ percent confidence interval for θ is given by:

$$\bar{x} \pm t_{\alpha/2, n-1} \frac{s}{\sqrt{n}}$$

Where the upper percentage $100(\alpha/2)$ point of the *t*-density function with n-1 degrees of freedom is denoted by $t_{\alpha/2, n-1}$, and *s* is the standard deviation of the sample. The following quantity is called the half-width of the confidence interval (Rossetti, 2009).

$$h = t_{\alpha/2, n-1} \frac{s}{\sqrt{n}}$$

The simulation model in this study is run for 50 replications to get fairly tight half-widths with 95% confidence. The output random variables for which the half-width analysis is implemented include average truck cycle times during day and night shifts, average waiting times at processing plants 1 and 2, and average utilizations of trucks and shovels. Table 53 presents the summary of statistics for these random output variables.

Table 53. Half-widths of random output variables

Random Output Variable	Sample Mean	Sample Standard Deviation	Half-width
Average Truck Cycle Time During Day Shifts (minutes)	16.00	0.21	0.06
Average Truck Cycle Time During Night Shifts (minutes)	17.66	0.20	0.06
Average Truck Waiting time at Processing Plant 1 (minutes)	2.25	0.31	0.09
Average Truck Waiting time at Processing Plant 2 (minutes)	2.32	0.26	0.07
Average Truck Utilization (%)	70.38	0.22	1.67
Average Shovel Utilization (%)	92.51	0.31	0.06

4.7 Summary and Remarks

In this chapter, the proposed simulation model has been implemented in a real open-pit mine. The optimal short-term schedule of the mine has been considered as the main input to the simulation model. Other input parameters such as stochastic variables have also been presented in this chapter.

The model has determined the initial numbers of trucks and shovels in conditions where equipment failures are ignored. Then, the numbers of trucks and shovels has been determined by taking into account equipment failures. Because equipment utilization varies during different periods, a maintenance schedule has been developed for trucks.

In the third part of this chapter, various system KPIs have been assessed in detail. The outputs of the simulation model have focused on tonnage, grades, utilizations, cycle times, waiting times, and queue lengths. Because the average waiting times at processing plants have been high, a new scenario has been introduced to reduce the average waiting times at processing plants.

The last parts of the chapter have dealt with verifying the model and assessing the replication number.

CHAPTER 5

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

This chapter contains the thesis summary and concluding statements. The benefits and contributions of this research are highlighted, as well as recommendations for future work in studying truck-and-shovel systems for material-handling-and-haulage, in conjunction with production plans.

5.1 Summary of Research

The economics of today's mining industry and the highly competitive mineral market force the mining industry to become more efficient, with attention focused on reducing operating costs. Especially in open-pit mines, achieving higher production with minimum cost is an essential issue, because open-pit mine operations are highly capital intensive.

Operating the equipment and machinery involved in material-handling-and-haulage systems is one of the primary contributors to the overall operating costs. Nowadays, mining companies try to reduce their operating costs by producing more with less equipment. As the mining industry is faced with equipment that is increasing in size and capacity, haul distances that are growing longer, and pits that are becoming deeper, the efficient use of equipment becomes more important. Trucks and shovels are the most commonly used equipment in open-pit mines to extract and haul the material. A lot of effort has been directed to utilize trucks and shovels efficiently, because this equipment has a great potential to create savings by reducing hauling, operating, and maintenance costs.

Studying a truck-and-shovel system is challenging because of the complexity of the system caused by the significant number of interactions between the system's entities and the uncertainties associated with the truck-and-shovel operations. Methods reported in the literature to study truck-and-shovel systems are classified as mathematical programming, simulation, and stochastic methods such as queuing theory. Current research focuses mainly on allocation and dispatching problems. The following list summarizes the major shortcomings of the current literature’s analysis of truck-and-shovel systems: (1) limitations in dealing with comprehensive details in the system; (2) treatment of stochastic variables as deterministic processes; (3) considering shovels as continuously working equipment, and modeling the system based on a shovel’s production requirements; (4) ignorance of characteristics of mining-blocks and extraction sequences; (5)limitations in dealing with the interactions between the truck-and-shovel system and other systems involved in mining operations. These inadequacies can cause inaccurate representation of the truck-and-shovel system, resulting in an incorrect assessment of the equipment’s performance.

To solve the limitations in dealing with truck-and-shovel systems, this research has developed and applied a stochastic simulation model with a direct link to the short-term production schedule. The research has also developed a MILP model to address the allocation problem.

This study’s objective is to develop, implement, and verify a simulation model to analyze the behavior of a truck-and-shovel haulage system in open-pit mining in conjunction with the optimal short-term plan. In such a system, material is extracted by shovels and hauled by trucks to different destinations that include waste dumps, processing plants, and stockpiles. The proposed model takes into account the stochastic variables of the system, which include truck velocity during day and night shifts, shovel velocity, shovel bucket capacity, load time, dump time, and failures of equipment and facilities.

In general, the development and implementation of the simulation framework has been undertaken in two different stages. In the first stage, the equipment selection problem is considered, in which the required numbers of trucks and shovels are determined. This stage is implemented both for conditions where failures are ignored and conditions where failures are considered. In addition, the possibility of building a maintenance schedule is evaluated. In the second stage, the system’s

KPIs are further assessed. The KPIs addressed in this research include total delivered material tonnage to each destination; average truck and shovel utilizations; average grades of elements such as magnetic iron, phosphor and sulfur; average truck waiting times; average truck queue lengths; and average truck cycle time. In addition, this research studies the possibility of improving the system.

Arena (Rockwell Automation, 2010) simulation software has been used to develop the model. The simulation model has been applied in a real open-pit mine with a mining capacity of 2.2 million tonnes per month. The mine's optimal short-term schedule is the basic input to the model, and the model captures the characteristics of the mining-cuts. The simulation is run for one year with a focus on monthly and shift-based KPIs. The results have been explained in detail in Chapter 4.

5.2 Conclusions

In pursuing this research, the literature review established the limitations in the current body of knowledge analyzing the truck-and-shovel system. The literature showed that there has never been any previous attempt to integrate truck-and-shovel system analysis with short-term or long-term production plans. The aforementioned limitations can affect the precise assessment of equipment performance, emphasizing the need for a tool that takes into consideration these deficiencies. Consequently, it is important that accurate models are developed to address these challenges. To contribute to the body of knowledge, this research pioneers the effort to use a simulation model linked to an optimal short-term production schedule while considering uncertainties associated with the operations of equipment.

The research objectives outlined in Chapter 1 have been achieved within the research scope. The following conclusions were drawn from the implementation of the simulation model framework for integrating truck-and-shovel operations with the optimal short-term production schedule:

- The simulation model has been developed with the appropriate level of detail, and many different aspects of truck-and-shovel operations have been explored. Arena (Rockwell Automation, 2010) simulation software has been used to implement the model on a real open-pit mine in which there are six different destinations that include two waste dumps, two stockpiles, and two processing plants. In the mine being studied, shovels extract material and load them to trucks. Then, trucks travel to the pit-exit point and from there to the proper destination. After dumping at the destination, trucks travel back to the pit-exit point.

- The simulation model has been linked to optimal short-term schedule. This approach guarantees that the operational plans will honor the short-term and long-term objectives. The optimal short-term production plan for this mine was developed for a time horizon of one year with monthly resolution. Total rock tonnage and ore tonnage of the mining-cuts was25 and 8 million tonnes, respectively.

- The simulation model considers stochastic variables in the truck-and-shovel system, and permits for the occurrence of random events, both of which are crucial in mine planning because of the level of uncertainty in mining operations. These uncertainties include the tonnage that a shovel can extract at each load-pass; the time that it takes to complete one load-pass; the time that it takes to complete the dumping action; moving velocity of a shovel during day and night shifts; velocity of a loaded truck and an empty truck during day and night shifts; and failures of trucks, shovels and crushers. Each stochastic variable has been represented with a probability density function. For most of the random variables, data analysis has been performed on historical dispatching data gathered from a Jigsaw dispatching database. To fit the best probability density function Arena Input Analyzer (Rockwell Automation, 2010) has been used, which implements the chi-square test and Kolmogorov-Smirnov test to fit the best probability density function on a set of data.

- The simulation model has been run for 50 replications to get fairly tight half-widths with 95% confidence. The output random variables for which the half-width analysis has been implemented include:
  - Average Truck Cycle Time During Day Shifts with the half-width 0.38% of the sample mean;
  - Average Truck Cycle Time During Night Shift with the half-width 0.34% of the sample mean;
  - Average Truck Waiting time at Processing Plant 1with the half-width 4% of the sample mean;
  - Average Truck Waiting time at Processing Plant 2 with the half-width 3.02% of the sample mean;
  - Average Truck Utilization with the half-width 2.37% of the sample mean; and
  - Average Truck Utilization with the half-width 0.06% of the sample mean.
- Required numbers of trucks and shovels have been determined in two conditions: (a) equipment does not fail and (b) equipment fails. Different scenarios have been generated using Arena Process Analyzer (Rockwell Automation, 2010). The variable under control was the numbers of trucks and shovels which were different in various scenarios. The criteria used to evaluate each scenario were the production level, average shovel utilization, and average truck utilization.

  When considering no failures, the best scenario has created 81% average shovel utilization and 84% average truck utilization. Two shovels and eight trucks have been used to build this scenario.

  When considering failures, the best scenario has created 89% average shovel utilization and 67% average truck utilization. Three shovels and 11 trucks have been used to build this scenario.

- Because of variations in average monthly equipment utilizations, a maintenance schedule has been developed for trucks. As a result, the mine has been planned to always use three shovels; 10 trucks in months 1, 3, 5, 7, 9; and 11 trucks in months 2, 4, 6, 8, 10, 12. The average shovel and truck utilizations have been measured as 93% and 71%, respectively.
- The simulation model studies queuing, equipment utilization, and production of mining operations. The model has produced all the desired information in detail to generate box plots or histograms. The following KPIs have been studied:
    - Average monthly shovel utilization, and average monthly truck utilization;
    - Delivered material tonnage to each destination
    - Average grade of magnetic iron, phosphor, and sulfur delivered to each destination;
    - Average waiting time at each destination, average monthly waiting time at processing plant 1, and average monthly waiting time at processing plant 2;
    - Average queue length at each destination, average monthly queue length at processing plant 1, and average monthly queue length at processing plant 2;
    - Average delivered material tonnage during some sample shifts, and failure durations for trucks, shovels, and crushers during those shifts; and
    - Average monthly truck cycle time during day shifts, and average monthly truck cycle time during night shifts.
- Because the truck waiting times were high, a new scenario was introduced and examined to reduce the waiting times and increase the system's performance. The new recommendation is that if a crusher has failed, no

trucks should travel to that processing plant. Instead, trucks should be redirected to the corresponding stockpile.

Although monthly ore production has varied (by less than ± 5%) from the actual targets, the average waiting times at processing plant 1 and 2 have been reduced by 99.81% and 99.80%, respectively. The average truck cycle times during day and night shifts have been reduced by 4.50% and 4.59% respectively.

- The stochastic model has been verified and proved to be sufficiently accurate to model truck-and-shovel operations from as short as a shift to as long as one year. The model can accurately simulate a system as large as the entire truck-and-shovel operation and as small as one loading unit.

  To verify the stochastic model, it has been shown the total ore and waste material tonnage is exactly as planned in the short-term schedule. In addition, it has been proved that the average grades of elements delivered to each destination are in compliance with the corresponding boundaries.

  For further analysis of the model's accuracy, the stochastic model has been transformed to a deterministic one, in which all failures are ignored and all random variables are replaced with their mean values. For sample mining-cuts, the number of truck visits and the components of truck cycle time have been measured and compared with the simulation results. Components of truck cycle time include the time that it takes the truck to:

  - Travel from the pit-exit point to the mining-cut's location;
  - Be fully loaded;
  - Travel to the predetermined destination;
  - Dump the load; and
  - Travel from the destination back to the pit-exit point.

- Excel.csv format files are used for input and output data. The system's random variables and other specifications can be easily adjusted to study any mine, production plan, or truck-and-shovel system. The Excel output provides additional ease of comparison between results.

5.3 Contributions of the Research

Because of the uncertainties associated with truck-and-shovel operations, this research has developed a stochastic simulation model to study the truck-and-shovel system with a link to the optimal short-term production schedule. The proposed model offers the following significant improvements over the previous research in the context of truck-and-shovel analysis:

- This is a pioneering effort to develop a simulation model that is directly linked to a short-term plan. This research contributes significantly to the body of knowledge on truck-and-shovel system analysis.
- Unlike other simulation studies that assume shovels as continuously working equipment, and model the system based on the shovel's production requirements, the proposed simulation model deals with mining-cuts. The model deals with each mining-cut's location, tonnage, and grades.
- This approach is also the first to takes into account the precedence between mining-cuts that has never been addressed before.
- Unlike mathematical programming methods, the simulation method takes into account the uncertainties associated with truck-and-shovel operations. These uncertainties include truck velocity during day and night shifts, shovel velocity, shovel bucket capacity, dump time, load time, and failures of equipment.
- The simulation model includes an appropriate level of detail. Many different aspects of truck-and-shovel operations have been explored. In addition, processes such as reclamation and events such as crusher failures are considered in the model.

5.4 Recommendations for Further Research

Although the truck-and-shovel simulation model developed in this thesis has provided pioneering efforts to analyze and improve the system in conjunction with optimal production plans, there is still the need for continued investigation into using simulation models in this context. The following recommendations could improve and add to the body of knowledge in this research area.

- The proposed simulation model assumes that all trucks and all shovels are identical. With this approach the equipment selection problem has been reduced to determining just the numbers of trucks and shovels. To deal with the problem comprehensively, the simulation model should be extended to include different types of trucks and shovels. Therefore, the simulation model should determine the required numbers of trucks and shovels as well as their types, to make the best matches between them.

- Although the simulation model is verified in this study, the validation process is recommended for further research. To validate the model, historical dispatching data should be gathered and analyzed for the mine same as for which the truck-and-shovel system is being studied. The model should be built based on the data during year n. Then, the model should be run for year $n+1$, and results should be compared with actual data of year $n+1$. For this purpose, actual data for two consecutive years must be available.

- Although the velocity of trucks and shovels during day and night shifts are stochastic variables, the simulation model assumes that the velocity during a cycle is fixed. To deal with this limitation, the model should be extended to consider the haul road profiles and different velocities in different segments of haul roads.

- The MILP model to deal with the allocation problem is theoretically formulated in this research. Verification and implementation of the model on synthetic data is recommended for further research.

- To push forward the frontiers of mining, further research should be carried out to integrate the proposed MILP model with the developed simulation model. The MILP model allocates the trucks and shovel to mining-faces, and results are put into the simulation model to imitate the behavior of trucks and shovels. The simulation model will call the MILP model to repeat the allocation optimization process when the state of the system changes, for example, when a failure occurs, a mining-face depletes, or a mine-planning period changes.

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APPENDICES

Appendix 1 Simulation Framework for Mining-cut Extraction Sequence

This section is concerned with explaining the logic used to deal with the mining-cut extraction sequence. The following steps explain the procedure. The case study is also explained as the example to further clear the method.

- The total number of mining-cuts is determined that is denoted with *m* $(i, k \in m)$.

- An extra dummy mining-cut is considered that is assumed to be completely extracted at the beginning of the simulation run. The ID number of *m*+1is assigned to it. This dummy mining-cut can be referred as air, and

- Based on the optimal short-term schedule, for each mining-cut the number of precedent mining-cuts is determined. The maximum number is chosen and denoted by *b* $(j \in b)$.

- For each mining-cut *b* attributes are defined as *a precedence 1*, *a precedence 2*, …, and *a precedence b*. The j^{th} attribute of the i^{th} mining-cut shows the ID of the j^{th} precedent mining-cut that should be extracted before mining-cut *i*.

  Not all of the mining-cut has *b* precedent mining-cuts. If a mining-cut has *c* precedent mining-cuts $(c < b)$, *b-c* attributes of this mining-cut are assigned ID of the dummy mining-cut, which is *m*+1.

- A 1-D array variable called *v1d precedence* is generated. This variable has one column and *m*+1 rows. The i^{th} row of the *v1d precedence* gets a binary value (0 and 1), and represents the status of the i^{th} mining-cut. If the i^{th} mining-cut is completely extracted it is 1, otherwise it is 0.

m+1th row is assigned value of 1 which is not changed during the simulation run. This cell is representative of the dummy mining-cut which is assumed to be completely extracted at the beginning of the simulation run.

- During the simulation run, when mining-cut i enters the system, the simulation reads the IDs of the precedent mining-cuts from the input Excel file, and assigns them to the aforementioned b attributes.
- The model checks if all precedent mining-cuts are extracted. For example, if one of the attributes gets the value of k, it means that mining-cut k should be extracted before the i^{th} mining-cut. The model goes to the k^{th} row of the variable *v1d precedence* and checks if the value of that row is 1.
- Also, during simulation run, if mining-cut i is extracted, the model changes the value of the i^{th} row of the variable *v1d precedence* from 0 to 1.

Example:

In the mine under study, 330 mining-cuts should be extracted during one year $(m = 330)$. A dummy mining-cut with ID 331 is considered as completely extracted at the beginning of the simulation run. In the short-term schedule of the mine under study, a mining-cut can have maximum 11 precedent mining-cuts $(b = 11)$.

For each mining-cut 11 attributes are assigned. For instance, mining-cut 153 has five precedent mining-cuts as 182, 186, 187, 188, and 191, which are assigned to attributes *a precedence 1* to *a precedence 5*. The remaining six attributes, *a precedence 6* to *a precedence 11* get the value of 331.

When this mining-cut enters the system, the model checks the 182nd, 186th, 187th, 188th, 191st, and 331st cells of the variable *v1d precedence*. If all cells are 1, then the mining-cut 153 can go through the system, otherwise it should wait until all cells are 1. It is obvious that the 331st cell is always 1.

After the mining-cut 153 is completely extracted, the model changes the 153rd cell of the variable *v1d precedence* from 0 to 1.

This process is repeated for all mining-cuts in the same manner.

Appendix 2 Entities, Resources, Attributes, and Variables

Entities:

ent block is the representative of a fraction of a mining-cut that is scheduled to be completely extracted at a specific period and be delivered to a predetermined destination. This entity is the major one that symbolizes the movement of a mining-cut by trucks and shovels.

ent dummy is a dummy entity used in sub-models to complete different tasks, such as: to deal with shift changes (adjusting *v shift*), to deal with period changes (adjusting *v period*), to write variables of interest into Text and Excel output files, and to calculate and record statistics related to failures of trucks and shovels.

ent reclamation is like a dummy entity that deals with the reclamation process and symbolizes the movement of material from stockpiles to processing plants.

Attributes:

a block number is the ID of an entity. The ID is assigned based on the entering sequence of entities to the simulation model. This number is different from the ID number included in the input data. The ID of a mining-cut in input data is the original ID of that mining-cut which is used in the scheduling phase.

a x is the x coordinate of the center of a mining-cut.

a y is the y coordinate of the center of a mining-cut.

a z is the z coordinate of the center of a mining-cut.

a block ton is the total tonnage of a mining-cut.

a fraction is the portion of a mining-cut that is going to be extracted at each period and delivered to each destination facility.

a destination is the destination code number where an entity is going to be delivered. It is assumed that there are 6 destination facilities available in the open-pit mine under study. Numbers 1 to 6 are considered as the destination code for the following destinations respectively: waste dump 1, waste dump 2, stockpile 1, stockpile 2, processing plant 1, and processing plant 2. This attribute is also used in the simulation model to determine the material type of content of mining-cuts. If *a destination* gets value of 1 or 2 it means that material will be delivered to waste dumps, so it is waste. If *a destination* gets value of 3 or 4 it means that material will be delivered to stockpiles, and if *a destination* gets value of 5 or 6 it means that material will be delivered to processing plants. In the later two situations the material type is ore.

a p is the phosphor grade of the mining-cut.

a s is the sulfur grade of the mining-cut.

a mwt is the magnetic weighted average of the mining-cut.

a dis exit is the distance between the center of a mining-cut and the pit-exit point. This distance is assigned based on the ramp used to haul the material.

a dis destination is the distance between a mining-cut and the destination where that mining-cut is delivered, and represents the travelling distance of an entity.

a period is the number of the period in which the entity is scheduled to be extracted.

a id is the original ID of that mining-cut which is used in the scheduling phase.

a precedence 1, *a precedence 2*, …, *a precedence 11* are the original IDs of the precedent mining-cuts of a mining-cut. Each mining-cut can have maximum 11 precedents.

a entity ton is the tonnage of an entity which is the portion of the mining-cut which is represented by the entity (*a block ton* multiplied by *a fraction*)

a remain ton is the remaining tonnage of an entity. When an entity enters the simulation model, the value of *a remain ton* assigned to the entity is equal to the total tonnage of the entity (*a entity ton*). Each digging action removes some tonnage of material causing deduction in the remaining tonnage. After a digging action *a remain ton* decreases by the tonnage that is removed from the entity (*a extraction ton*). When this attribute equals to 0 the corresponding mining-cut is assumed to be completely extracted.

a load number is the number of load-passes for a truck. Each load-pass increases *a load number* by one unit. Since it is assumed that a truck is fully loaded by 3 load-passes, after 3 load-passes when truck leaves the entity, *a load number* is reset to 0 for the next truck.

a which shovel holds the index number of the shovel that is seized by the entity. This index could have the value of 1 to 5 according to whichever member of the set of shovels (*rs shovel set*) is selected.

a which truck holds the index number of the truck that is seized by an entity. This index may have the value of 1 to 15 according to whichever member of the set of trucks (*rs truck set*) is selected.

a start time truck cycle holds the starting time of a truck's cycle when the truck is seized by an entity. This attribute gets the value of *TNOW* when the truck starts to travel to the mining-cut.

a start shift truck cycle indicates the shift in which the cycle of a truck starts. It gets the value of 1 if the truck's cycle starts at a day shift, and gets the value of 2 if the truck's cycle starts at a night shift.

a start time load cycle holds the starting time of a loading cycle. This attribute gets the value of *TNOW* when a shovel starts to dig into the mining-cut. The loading cycle consists of the swing motion, digging, and loading operations included in three load-passes.

a extraction ton holds the tonnage extracted during one load-pass. If the remaining tonnage of an entity (*a remain ton*) is more than the shovel bucket capacity, the shovel extracts the tonnage according to its capacity which is maximum 40 tonnes. If the remaining tonnage of an entity (*a remain ton*) is less than the shovel bucket capacity, the shovel extracts what is left (*a remain ton*).

a truck ton calculates the tonnage of material loaded to a truck. During the loading process, this attribute increases by *a extraction ton* in each load-pass. After 3 load-passes, when the truck leaves the mining-cut, this value remains unchanged until the truck dumps its load. At this point, *a truck ton* is reset to 0 for that truck.

a return exit dis holds the distance between the destination and the pit-exit point. After dumping, a truck should travel this distance to return to the pit entrance. Based on the destination where the material is delivered, this attribute gets different values.

Variables:

Single element variables:

v block number counts the number of mining-cuts that enter the simulation model.

v input ton sums up the total tonnage of entities entering the system.

v period is the number of current period during the simulation run.

v extracted ore sums up the total tonnage of extracted ore material.

v extracted waste sums up the total tonnage of extracted waste material.

v shift changes with the simulation clock and shows the current shift. It gets the value of 1 if it is a day shift and gets the value of 2 if it is a night shift.

v reclamation material number counts the number of reclamation entities (*ent reclamation*) that enter the simulation model.

v yearly ore tonnage sums up the total tonnage of ore material delivered to the stockpiles and processing plants throughout the whole replication. This variable is useful in the first phase of methodology which is scenario analysis.

v yearly waste tonnage sums up the total tonnage of waste material delivered to the waste dumps throughout the whole replication. This variable is useful in the first phase of methodology which is scenario analysis.

v total shovel utl calculates the average shovel utilization throughout the whole replication. This variable is useful in the first phase of methodology which is scenario analysis. In each scenario, this variable sums up the all shovels' utilizations and divides it to the number of available shovels in that specific scenario.

v total truck utl calculates the average truck utilization throughout the whole replication. This variable is useful in the first phase of methodology which is scenario analysis. In each scenario, this variable sums up the all trucks' utilizations and divides it to the number of available trucks in that specific scenario.

1-D array variables:

v1d precedence is a 1-D array with 1 column and 331 rows. 331 is the number of mining-cut entities + 1. Each cell of *v1d precedence* represents the status of the corresponding mining-cut and gets a binary value (0 and 1). If a mining-cut is completely extracted the corresponding cell is 1, otherwise it is be 0. The cell at row 331 is assigned value of 1 and it would not change during the simulation run. This cell is a representative of a dummy mining-cut which is assumed to be completely extracted at the beginning of the model.

v1d input ore has 1 column and 12 rows, each row representative of a period (month). A cell sums up the total ore tonnage of entities entering the system during corresponding period.

v1d input waste has 1 column and 12 rows, each row representative of a period (month). A cell sums up the total waste tonnage of entities entering the system during corresponding period.

v1d wd1 p has 1 column and 12 rows, each row representative of 1 period (month). The element of each row calculates the average phosphor grade delivered to the waste dump 1 during the corresponding period.

v1d wd1 s has 1 column and 12 rows, each row representative of 1 period (month). The element of each row calculates the average sulfur grade delivered to the waste dump 1 during the corresponding period.

v1d wd1 mwt has 1 column and 12 rows, each row representative of 1 period (month). The element of each row calculates the magnetic weighted average grade delivered to the waste dump 1 during the corresponding period.

v1d wd1 ton has 1 column and 12 rows, each row representative of 1 period (month). The element of each row calculates the total material tonnage delivered to the waste dump 1 during the corresponding period.

v1d wd2 p has 1 column and 12 rows, each row representative of 1 period (month). The element of each row calculates the average phosphor grade delivered to the waste dump 2 during the corresponding period.

v1d wd2 s has 1 column and 12 rows, each row representative of 1 period (month). The element of each row calculates the average sulfur grade delivered to the waste dump 2 during the corresponding period.

v1d wd2 mwt has 1 column and 12 rows, each row representative of 1 period (month). The element of each row calculates the magnetic weighted average grade delivered to the waste dump 2 during the corresponding period.

v1d wd2 ton has 1 column and 12 rows, each row representative of 1 period (month). The element of each row calculates the total material tonnage delivered to the waste dump 2 during the corresponding period.

v1d sp1 p has 1 column and 12 rows, each row representative of 1 period (month). The element of each row calculates the average phosphor grade delivered to the stockpile 1 during the corresponding period.

v1d sp1 s has 1 column and 12 rows, each row representative of 1 period (month). The element of each row calculates the average sulfur grade delivered to the stockpile 1 during the corresponding period.

v1d sp1 mwt has 1 column and 12 rows, each row representative of 1 period (month). The element of each row calculates the magnetic weighted average grade delivered to the stockpile 1 during the corresponding period.

v1d sp1 ton has 1 column and 12 rows, each row representative of 1 period (month). The element of each row calculates the total material tonnage delivered to the stockpile 1 during the corresponding period.

v1d sp2 p has 1 column and 12 rows, each row representative of 1 period (month). The element of each row calculates the average phosphor grade delivered to the stockpile 2 during the corresponding period.

v1d sp2 s has 1 column and 12 rows, each row representative of 1 period (month). The element of each row calculates the average sulfur grade delivered to the stockpile 2 during the corresponding period.

v1d sp2 mwt has 1 column and 12 rows, each row representative of 1 period (month). The element of each row calculates the magnetic weighted average grade delivered to the stockpile 2 during the corresponding period.

v1d sp2 ton has 1 column and 12 rows, each row representative of 1 period (month). The element of each row calculates the total material tonnage delivered to the stockpile 2 during the corresponding period.

v1d pr1 p has 1 column and 12 rows, each row representative of 1 period (month). The element of each row calculates the average phosphor grade delivered to the processing plant 1 during the corresponding period.

v1d pr1 s has 1 column and 12 rows, each row representative of 1 period (month). The element of each row calculates the average sulfur grade delivered to the processing plant 1 during the corresponding period.

v1d pr1 mwt has 1 column and 12 rows, each row representative of 1 period (month). The element of each row calculates the magnetic weighted average grade delivered to the processing plant 1 during the corresponding period.

v1d pr1 ton has 1 column and 12 rows, each row representative of 1 period (month). The element of each row calculates the total material tonnage delivered to the processing plant 1 during the corresponding period.

v1d pr2 p has 1 column and 12 rows, each row representative of 1 period (month). The element of each row calculates the average phosphor grade delivered to the processing plant 2 during the corresponding period.

v1d pr2 s has 1 column and 12 rows, each row representative of 1 period (month). The element of each row calculates the average sulfur grade delivered to the processing plant 2 during the corresponding period.

v1d pr2 mwt has 1 column and 12 rows, each row representative of 1 period (month). The element of each row calculates the magnetic weighted average grade delivered to the processing plant 2 during the corresponding period.

v1d pr2 ton has 1 column and 12 rows, each row representative of 1 period (month). The element of each row calculates the total material tonnage delivered to the processing plant 2 during the corresponding period.

v1d waste p has 1 column and 12 rows, each row representative of 1 period (month). The element of each row calculates the average phosphor grade delivered to the both waste dumps during the corresponding period.

v1d waste s has 1 column and 12 rows, each row representative of 1 period (month). The element of each row calculates the average sulfur grade delivered to the both waste dumps during the corresponding period.

v1d waste mwt has 1 column and 12 rows, each row representative of 1 period (month). The element of each row calculates the magnetic weighted average grade delivered to the both waste dumps during the corresponding period.

v1d waste ton has 1 column and 12 rows, each row representative of 1 period (month). The element of each row calculates the total material tonnage delivered to the both waste dumps during the corresponding period.

v1d stock p has 1 column and 12 rows, each row representative of 1 period (month). The element of each row calculates the average phosphor grade delivered to the both stockpiles during the corresponding period.

v1d stock s has 1 column and 12 rows, each row representative of 1 period (month). The element of each row calculates the average sulfur grade delivered to the both stockpiles during the corresponding period.

v1d stock mwt has 1 column and 12 rows, each row representative of 1 period (month). The element of each row calculates the magnetic weighted average grade delivered to the both stockpiles during the corresponding period.

v1d stock ton has 1 column and 12 rows, each row representative of 1 period (month). The element of each row calculates the total material tonnage delivered to the both stockpiles during the corresponding period.

v1d mill p has 1 column and 12 rows, each row representative of 1 period (month). The element of each row calculates the average phosphor grade delivered to the both processing plants during the corresponding period.

v1d mill s has 1 column and 12 rows, each row representative of 1 period (month). The element of each row calculates the average sulfur grade delivered to the both processing plants during the corresponding period.

v1d mill mwt has 1 column and 12 rows, each row representative of 1 period (month). The element of each row calculates the magnetic weighted average grade delivered to the both processing plants during the corresponding period.

v1d mill ton has 1 column and 12 rows, each row representative of 1 period (month). The element of each row calculates the total material tonnage delivered to the both processing plants during the corresponding period.

v1d sp2topr2 mwt has 1 column and 12 rows, each row representative of 1 period (month). The element of each row calculates the magnetic weighted average grade reclaimed from stockpile 2 and delivered to processing plant 2 during the corresponding period. Since material are reclaimed only from stockpile 2 and stockpile 2 can feed only processing plant 2, there is no need to have more of this variable.

v1d sp2topr2 ton has 1 column and 12 rows, each row representative of 1 period (month). The element of each row calculates the total material tonnage reclaimed from stockpile 2 and delivered to processing plant 2 during the corresponding period. Since material are reclaimed only from stockpile 2 and stockpile 2 can feed only processing plant 2, there is no need to have more of this variable.

2-D array variables:

v2d shovel coordinate has 5 rows and 3 columns. Each row is a representative for a shovel and columns respectively are the x, y, and z coordinates of the corresponding shovel's location. When a shovel is seized by a mining-cut and moves to that mining-cut, a new coordinates are assigned to that shovel, so the cells of the row representing the shovel gets new values.

v2d waste p shift has 2 columns and 12 rows, each row representative of 1 period (month), first column indicator of the day shift, and second column showing the night shift. Each element calculates the average phosphor grade delivered to the both waste dumps during the according period and shift.

v2d waste s shift has 2 columns and 12 rows, each row representative of 1 period (month), first column indicator of the day shift, and second column showing the night shift. Each element calculates the average sulfur grade delivered to the both waste dumps during the according period and shift.

v2d waste mwt shift has 2 columns and 12 rows, each row representative of 1 period (month), first column indicator of the day shift, and second column showing the night shift. Each element calculates the magnetic weighted average grade delivered to the both waste dumps during the according period and shift.

v2d waste ton shift has 2 columns and 12 rows, each row representative of 1 period (month), first column indicator of the day shift, and second column showing the night shift. Each element calculates the total material tonnage delivered to the both waste dumps during the according period and shift.

v2d stock p shift has 2 columns and 12 rows, each row representative of 1 period (month), first column indicator of the day shift, and second column showing the night shift. Each element calculates the average phosphor grade delivered to the both stockpiles during the according period and shift.

v2d stock s shift has 2 columns and 12 rows, each row representative of 1 period (month), first column indicator of the day shift, and second column showing the night shift. Each element calculates the average sulfur grade delivered to the both stockpiles during the according period and shift.

v2d stock mwt shift has 2 columns and 12 rows, each row representative of 1 period (month), first column indicator of the day shift, and second column showing the night shift. Each element calculates the magnetic weighted average grade delivered to the both stockpiles during the according period and shift.

v2d stock ton shift has 2 columns and 12 rows, each row representative of 1 period (month), first column indicator of the day shift, and second column showing the night shift. Each element calculates the total material tonnage delivered to the both stockpiles during the according period and shift.

v2d mill p shift has 2 columns and 12 rows, each row representative of 1 period (month), first column indicator of the day shift, and second column showing the night shift. Each element calculates the average phosphor grade delivered to the both processing plants during the according period and shift.

v2d mill s shift has 2 columns and 12 rows, each row representative of 1 period (month), first column indicator of the day shift, and second column showing the night shift. Each element calculates the average sulfur grade delivered to the both processing plants during the according period and shift.

v2d mill mwt shift has 2 columns and 12 rows, each row representative of 1 period (month), first column indicator of the day shift, and second column showing the night shift. Each element calculates the magnetic weighted average grade delivered to the both processing plants during the according period and shift.

v2d mill ton shift has 2 column and 12 rows, each row representative of 1 period (month), first column indicator of the day shift, and second column showing the night shift. Each element calculates the total material tonnage delivered to the both processing plants during the according period and shift.

v2d shovel utl has 5 columns and 12 rows, each row representative of 1 period (month), and each column showing 1 shovel. Each element records the average of a defined statistic throughout the replication for the corresponding shovel and period. The defined statistic calculates the shovel utilization periodically (monthly). This statistic is defined by using dstat expression *ResUtil* and collecting statistics of resource utilization every 30 days (monthly). For example, the element of the 5th row and 3rd column refers to the average monthly utilization of shovel 3 during the first 5 months.

v2d truck utl has 15 columns and 12 rows, each row representative of 1 period (month), and each column showing 1 truck. Each element records the average of a defined statistic throughout the replication for the corresponding truck and period. The defined statistic calculates the truck utilization periodically (monthly). This statistic is defined by using dstat expression *ResUtil* and collecting statistics of resource utilization every 30 days (monthly). For example, the element of the 5th row and 3rd column refers to the average monthly utilization of truck 3 during the first 5 months.

v2d shift 1 shovels utl has 5 columns and 12 rows, each row representative of 1 period (month), and each column showing 1 shovel. Each element records the average of a defined statistic throughout the replication for the corresponding shovel and period. The defined statistic calculates the shift shovel utilization for day shifts. This statistic is defined by using dstat expression *ResUtil* and collecting statistics of resource utilization during day shifts. For example, the element of the 5th row and 3rd column refers to the average day shift utilization of shovel 3 during the first 5 months.

v2d shift 2 shovels utl has 5 columns and 12 rows, each row representative of 1 period (month), and each column showing 1 shovel. Each element records the average of a defined statistic throughout the replication for the corresponding shovel and period. The defined statistic calculates the shift shovel utilization for night shifts. This statistic is defined by using dstat expression *ResUtil* and collecting statistics of resource utilization during night shifts. For example, the element of the 5th row and 3rd column refers to the average night shift utilization of shovel 3 during the first 5 months.

v2d shift 1 trucks utl has 15 columns and 12 rows, each row representative of 1 period (month), and each column showing 1 truck. Each element records the average of a defined statistic throughout the replication for the corresponding truck and period. The defined statistic calculates the shift truck utilization for day shifts. This statistic is defined by using dstat expression *ResUtil* and collecting statistics of resource utilization during day shifts. For example, the element of the 5th row and 3rd column refers to the average day shift utilization of truck 3 during the first 5 months.

v2d shift 2 trucks utl has 15 columns and 12 rows, each row representative of 1 period (month), and each column showing 1 truck. Each element records the average of a defined statistic throughout the replication for the corresponding truck and period. The defined statistic calculates the shift truck utilization for night shifts. This statistic is defined by using dstat expression *ResUtil* and collecting statistics of resource utilization during night shifts. For example, the element of the 5th row and 3rd column refers to the average night shift utilization of truck 3 during the first 5 months.

v2d final shovels utl has 5 columns and 12 rows, each row representative of 1 period (month), and each column showing 1 shovel. Each element shows the average utilization of the corresponding shovel during only the corresponding period. For example, the element of the 5th row and 3rd column refers to the average utilization of shovel 3 during the 5th month.

v2d final trucks utl has 15 columns and 12 rows, each row representative of 1 period (month), and each column showing 1 truck. Each element shows the average utilization of the corresponding truck during only the corresponding period. For example, the element of the 5th row and 3rd column refers to the average utilization of truck 3 during the 5th month.

Sets and Resources:

rs shovel set is the set of shovels. 5 shovels are defined as the members of this resource set as follows: *rs shovel 1*, *rs shovel 2*, *rs shovel 3*, *rs shovel 4*, and *rs shovel 5*. In the first phase of the method, the numbers of trucks and shovels are determined. In this phase, in different scenarios different numbers of shovels out of these 5 shovels are considered as available.

rs truck set is the set of trucks. 15 trucks are defined as the members of this resource set as follows: *rs truck 1*, *rs truck 2*, … , and *rs shovel 15*. In the first phase of the method, the numbers of trucks and shovels are determined. In this phase, in different scenarios different numbers of trucks out of these 15 trucks are considered as available.

r waste dump 1 is the representative of the first waste dump. There is room for 3 only trucks to dump at the same time at this facility.

r waste dump 2 is the representative of the second waste dump. There is room for only 3 trucks to dump at the same time at this facility.

r stockpile 1 is the representative of the first stockpile. There is room for only 1 truck to dump at the same time at this facility.

r stockpile 2 is the representative of the second stockpile. There is room for only 1 truck to dump at the same time at this facility.

r process 1 is the representative of the first processing plant. There is room for only 1 truck to dump at the same time at this facility.

r process 2 is the representative of the first processing plant. There is room for only 1 truck to dump at the same time at this facility.

r loader is the loader that is used to load material to the truck during the reclamation process.

r rec truck is the truck that is used to transfer material from stockpiles to processing plant during the reclamation process.